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16. ABSTRACT

The second generation Regional Oxidant Model (ROM2) ~~is~~ was used to simulate ozone concentrations in the Northeastern United States over two week periods in each of three months: April, July and August 1980. In each period three separate model simulations ~~are~~ were performed. The first of these, the base case, used the 1980 NAPAP 5.3 emissions inventory to specify anthropogenic hydrocarbon and NO_x emissions. The second simulation, Control Strategy #1, assumed county-specific reductions of 5% to 50% in hydrocarbon emissions and the third simulation, Control Strategy #2, reduced VOC emissions from Control Strategy #1 an additional 22% across the board. In all three simulations the NO_x emissions ~~are~~ were the same and the hydrocarbon emissions from natural sources ~~are~~ were identical. The predicted ozone changes that result from the emissions changes ~~are~~ were extrapolated from the three, 2-week periods to the "ozone season", which begins on 1 April and runs through 31 October. ~~The extrapolation is performed using a technique developed in this paper.~~ Three general conclusions ~~are~~ were drawn: (1) reducing hydrocarbon emission rates generally reduces ozone levels; (2) the emissions changes proposed in control strategies 1 and 2 reduce peak O_3 concentrations most -- they have virtually no effect on concentrations below about the 95-percentile level; (3) the impact of controls on ozone levels is sensitive to meteorological conditions.

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AFFILIATION

Dr. Lamb is on assignment to the Meteorology and Assessment Division, Atmospheric Sciences Research Laboratory, from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

ABSTRACT

The second generation Regional Oxidant Model (ROM2) is used to simulate ozone concentrations in the Northeastern United States over two week periods in each of three months: April, July and August 1980. In each period three separate model simulations are performed. The first of these, referred to as the base case, used the 1980 NAPAP 5.3 emissions inventory to specify anthropogenic hydrocarbon and NO_x emissions. The second simulation, referred to as Control Strategy #1, assumed reductions of 5% to 50% in hydrocarbon emissions depending on the county in which sources are located. The third simulation, Control Strategy #2, used the same emissions as Control Strategy #1 but with hydrocarbon emission rates reduced an additional 22% across the board. In all three simulations the NO_x emissions are the same and the hydrocarbon emissions from natural sources are identical.

The predicted ozone changes that result from the emissions changes are extrapolated from the three, 2-week periods to the "ozone season", which begins on 1 April and runs through 31 October. The extrapolation is performed using a technique developed in this paper. Three general conclusions are drawn: (1) reducing hydrocarbon emission rates generally reduces ozone levels; (2) the emissions changes proposed in control strategies 1 and 2 reduce peak O_3 concentrations most -- they have virtually no effect on concentrations below about the 95-percentile level; (3) the impact of controls on ozone levels is sensitive to meteorological conditions. These and other results of the model simulations are discussed.

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SECTION 1

INTRODUCTION

The Regional Oxidant Model (ROM) was developed to assist the formulation of emissions control strategies for attaining the primary ozone standard. Since the primary standard is expressed in terms of a maximum one-hour averaged ozone value that is not to be exceeded more than once per year, the ROM was designed to simulate hourly concentrations under meteorological conditions associated with the highest ozone levels during a year. Typically, these conditions span a period of one to two weeks in the summer months. A model capable of simulating concentrations with hourly resolution is often referred to as an episodic model.

Recently, efforts to promulgate a secondary ozone standard, which would protect crops and forests, have created the need for a seasonal ozone model; specifically, a model capable of estimating the effects of emissions changes on the frequency of multi-hour averaged ozone concentrations during the seven-month period from 1 April to 31 October of each year. There are three basic ways of modeling seasonal concentration statistics.

One way is to derive a model from first principles that yields the desired information directly. Unfortunately, intractable theoretical problems are encountered in this approach which necessitate the adoption of fundamental assumptions that severely undermine the credibility of the model itself. Models of this type are of academic interest, but in the author's view they are not scientifically sound bases for developing costly

emissions control policies.

A second method of modeling seasonal concentrations is to run an episodic model for selected short period intervals within the season, and then "extrapolate" the results to the entire season. This is the approach that we will develop in this paper. This method also requires the adoption of basic assumptions but their impact on the accuracy of the model overall can be controlled to a large extent through proper design of the extrapolation scheme and judicious selection of the subinterval episodes.

The third and most accurate way of generating seasonal concentration statistics is simply to run an episodic model for the entire season. This brute force approach is presently impractical in the case of a model like the ROM that requires 2 hours of CPU time on an IBM 3090 mainframe computer to simulate a single day. However, this technique will eventually become feasible as computing power continues to increase and computing costs continue to decline. The author's laboratory is currently engaged in a research program with the Research Triangle Institute to develop a computer hardware module that can be attached to a VAX minicomputer to accelerate the execution speed of the ROM by a factor of 10 to 100. One objective of this project is to allow applications of the ROM to a full season. Another is to utilize the ROM in the development of optimal air pollution control strategies.

The principal objective of the present report is to describe estimated effects of VOC emissions changes on seasonal ozone levels in the Northeastern United States. The study is based on ROM simulations of three, 2-week episodes in April, July and August of 1980, extrapolated to the ozone

season, 1 April - 31 October, using a scheme described in Section 3 of this report. Each of the three episodes was simulated (and the results extrapolated to the season) for each of three emissions distributions: the 1980 NAPAP 5.3 inventory which is used as the base, or reference, case; and two "control strategies". The latter consist of different percentage changes in VOC emissions that could be achieved under control plans contained in the 1982 SIPs (described in detail later in Section 5).

The model results presented here are regarded only as interim estimates, partly because they are based on a very simplified implementation of the seasonal extrapolation scheme (developed in Section 3); and partly because the 1980 emissions inventory, which is used as the base state in these simulations, is not regarded to be of high enough quality to serve as a basis for control strategy development. Furthermore, the verification analyses of the ROM are not yet complete and therefore the accuracy of the model has not yet been established. Both the ROM verification studies and the development of a significantly improved emissions inventory (for 1985) are expected to be completed by late 1988.

In the next section we summarize the basic features of the Regional Oxidant Model. In Section 3 we develop the seasonal extrapolation method and we describe a simple implementation of it. In subsequent sections we use the scheme to infer seasonal benefits of emissions controls from model simulations of selected periods within the season.

SECTION 2

BASIC FEATURES OF THE REGIONAL OXIDANT MODEL

In this Section we describe basic features of the Regional Oxidant Model in very general terms. More detailed descriptions are available in Lamb (1983, '84a).

As we noted in the introduction the ROM was developed to assist the development of emissions control strategies for attaining the primary ozone standard. The EKMA and airshed models served this role in the early and mid 1970's; but by the end of the '70's it was realized that the ozone phenomenon covers much larger time and space scales than either of these models can handle. Thus, the ROM was developed to allow explicit treatment of the chemical and physical processes that are important in multi-day, long-range transport of ozone and its precursors, including biogenic hydrocarbons. Figure 1 (page 14) shows the spatial areas simulated by the ROM in studies now underway of the Northeastern and Southeastern United States. (Typical spatial areas covered by the Airshed and EKMA models are also illustrated for comparison.)

The spatial domain is divided into 2520 grid "squares", roughly 19 km on a side. The dots in Figure 1 mark the corners of the grid squares. Each grid cell is divided into 3 1/2 vertical levels, or grid cells, of varying thickness. Clouds fluxes, variations of wind speed and direction, mountain effects, inversions, turbulent mixing and other meteorological processes are simulated by each layer (see Figure, 2 page 15).

The thickness of each grid cell can change each hour of the simulated period to track changes in local meteorological conditions.

Within each of its 7560 grid cells the ROM keeps track of the concentrations of each of 28 chemical species listed in Table 1 (page 6), one of which is ozone, and 70 chemical reactions among various combinations of these species. The description of the chemistry used in the ROM is known as the Carbon Bond IV mechanism (Whitten and Gery, 1986). The rates of the reactions are functions of the local temperature, air density, humidity, sun angle, and cloud cover in each cell at each hour.

The land area within each grid square is partitioned into sub-areas according to land usage, e.g., urban land, agricultural land, deciduous forest land, water, and five other categories. This information is used to estimate surface heat fluxes and drag coefficients needed in the treatment of the turbulence effects. It serves also in the treatment of dry deposition of each of the 28 species.

Emission rates of each primary species from both anthropogenic and biogenic sources in each grid cell are also determined. The anthropogenic source strengths are based on state and county inventories of fuel usage, traffic counts, chemical processing, electric power production, wood burning and many other processes (Toothman, et al, 1984). Figure 3 (page 16) shows the top fifty hydrocarbon (VOC) and the top fifty nitrogen oxides (NO_x) emitting counties in the Northeastern U.S. based on 1980 emissions density data (anthropogenic only). Thirty counties are members of both sets, so the two groups combined contained only 70 rather than

TABLE 1. SUMMARY OF THE CHEMICAL SPECIES SIMULATED IN THE ROM USING THE CARBON BOND IV MECHANISM

Group	Species Name	Compounds Represented
Organics:	ETH	Ethene
	FORM	Formaldehyde
	ALD2	Acetaldehyde
	PAR	1-Carbon Paraffin Group
	OLE	2-Carbon Double Bond Group
	MGLY	Methylglyoxal
	PAN	$CH_3CO_3NO_2$
	C2O3	CH_3CO_3
	TLA	Tolualdehyde
	TOL	Toluene
	XYL	Xylene
	PHEN	Phenyl-type Product (cresol for toluene)
	ISOP	Isoprene
	PHO	Phenoxy Radical
	XO2	"Universal" Peroxy Radical (XO2 + NO → NO_2)
	XO2N	Nitrated Peroxy Intermediate (from isoprene + NO_3)
Inorganics:	CO	
	NO	
	NO_2	
	NO_3	
	N_2O_5	
	HONO	
	HNO_3	
	O	
	O_3	
	OH	
	HO_2	
	H_2O_2	

100 counties. These 70 counties produce about one-half of all anthropogenic VOC and NO_x emissions in the model area (Figure 1) excluding Canada. The county emissions data are apportioned to the model's grid squares using population distribution and other information. Emissions of major point sources are apportioned to vertical layers on the basis of plume rise calculations performed each hour for each source individually.

The emission rates of the biogenic hydrocarbons are based on estimates of the dry foliar mass of 61 species of trees, 10 types of field crops and two groups of grasses compiled for each grid cell from detailed Forest and Agricultural Service records. The biomass data are combined with empirical emissions factors for each species and hourly temperature, sunlight and cloud cover data to yield biogenic hydrocarbon emissions rates that vary hourly depending on local weather conditions in each grid square (see Novak and Reagan, 1986). Figure 4 (page 17) gives a general view of the spatial distribution of biogenic hydrocarbon sources. This figure shows the emission rate of the lumped species OLE, which is used in the model along with PAR as a surrogate of monoterpenes. The emission rates shown in the figure are for a midday hour when the biogenic sources are most active. The counties designated in Figure 3 (page 16) as major VOC emitters are the primary anthropogenic sources of the lumped species OLE.

The final basic set of input data required by the ROM is meteorological information: temperature, humidity, wind speed and direction, etc. These data are gathered from weather records of historical episodes, usually of several weeks duration, when maximum ozone levels were observed. Basic features of the ROM are summarized in Table 2 (page 8).

TABLE 2. REGIONAL OXIDANT MODEL (ROM) SPECIFICATIONS

Spatial:	1100 x 800 km domain ~ 18.5 x 18.5 horizontal grid resolution 3 1/2 variable thickness layers
Time:	6 - 30 day periods (practical limits) 30 min time resolution
Inputs:	Land use (9 categories) Anthropogenic emissions 8 hydrocarbon classes NO, NO_2, CO, etc. Biogenic hydrocarbon emissions Isoprene Monoterpenes Meteorological data winds, temperature, cloud info., etc. Initial and boundary concentrations
Outputs:	Concentrations of each of 28 species (O_3, NO, CO, FORM, XYL...) In each of 7560 grid cells Every 30 min of simulated period

The predictions of all models are subject to uncertainties and these must be taken into consideration in judging the significance of model results. Table 3 (page 13) lists the major sources of uncertainty in a model like the ROM. It is also essential in model applications to understand the type of information that the model is capable of providing. This knowledge is important not only for the "decision makers" who rely on the model as an information resource, but also for the model developers faced with the task of establishing performance standards for model evaluation studies. In this regard the output of any model can be classified into one of two categories: deterministic or stochastic. Without elaboration we state simply that the ROM is a model of the stochastic type (see Lamb, 1984, '86; and Lamb and Hati, 1987; for further details). Consequently, the ROM should be looked upon as a means of predicting concentration frequencies, spatial patterns in mean values and frequencies, and similar statistical information rather than a means of predicting the concentration that will occur at a specific place at a specific time. This restriction is not inconsistent with the objectives of ozone modeling which, in applications related to the primary standard, is to determine the frequency with which concentrations will exceed a given level.

Accordingly, we offer here as an interim measure of the ROM's performance a comparison of the cumulative frequency distribution of predicted hourly-averaged ozone concentrations in the period 14 July to 26 July 1980 with the corresponding distribution of observed concentrations at 215 SAROAD and Canadian monitoring stations. The comparisons are given in Figure 5a, page 18, in the form of quantile-quantile (QQ) plots. In these graphs the ordinate of a point (represented by a + or a digit)

is the concentration associated with the specified quantile of the distribution of predicted values while the abscissa is the corresponding concentration in the observations. If the frequency distributions of the predictions and observations were identical, the points of the QQ plot would lie along the straight line shown in each of the graphs. The dashed lines mark the area within which the quantiles of the predicted and observed values agree within ±10%.

For reasons associated with the stochastic nature of the ROM output, the data have been divided into three groups depending in part on the proximity of the measuring station to major NO_x or VOC sources. The group labeled "near source" (the top panel of Figure 5a) consists of stations located within or adjacent to ROM grid cells containing major sources. The group labeled "remote" contains stations that are farthest from major sources. The "intermediate" group contains all stations in between these extremes, and it contains the bulk of the data -- 185 of 215 stations.

There are two disparities between the predicted and observed concentration data that will tend to bias the comparisons. One is that the measurements are made at points in space whereas the predictions represent volume averages over grid cells, which are roughly 20 km on a side and 100 meters or so deep. Thus, in areas where there are significant spatial variations in ozone concentration of scales smaller than 20 km, point measurements would tend to scatter on either side of precise predictions. The second disparity is that the predicted values plotted in Figure 1 are from Layer 1 of the model rather than the surface layer, Layer 0, where the measurements are taken. The Layer 0 concentrations are

provided by a post-processor of the ROM which is not yet operational. Under stable nighttime conditions the Layer 1 ozone concentrations may be considerably higher than those in Layer 0 due to the effects of deposition. Therefore, to minimize bias we use only data from the daylight hours 0800-1800 in the comparisons.

The relationship between the predicted and observed concentrations evident in Figure 5a follows the general pattern we just outlined: underestimation of peak values and overestimation of minima. This trend is most pronounced at points near major sources, where one would expect the largest small scale spatial fluctuations. At the remote sites, where one would expect the least effect of fluctuations, the frequency distributions of the observed and predicted values agree to within ±10% from roughly the 40-th percentile up to the maximum value, or 100-th percentile. The accentuated overprediction of low concentrations at the remote sites is apparently due to the close proximity of most of these receptors to the lateral boundaries of the ROM. Specifying the inflow boundary concentrations in a model of this scale is fraught with uncertainty. At the intermediate range sites, agreement within ±10% exists from about the 60-th to the 99-th percentiles. Figure 5(b and c), (page 19) provides a measure of the ROM's accuracy in predicting the spatial pattern of maximum ozone. Figure 5(b) shows the maximum 1-hour averaged O_3 concentration (ppb units) measured at some 200 SAROAD monitoring sites in the Northeast during the period 12-17 July 1980. Figure 5(c) shows the corresponding model predictions, considering only the predictions at the monitoring station sites.

A thorough evaluation of the ROM is now underway using 50 days of simulated ozone, NO_x and hydrocarbon concentrations and observed data from both SAROAD and the 1980 NEROS field study. The results will be reported in 1988. A major problem faced by the model evaluation effort is that it is virtually impossible to test the performance of the model in the role in which it will be applied, namely estimating the concentration changes that will result from specified emissions changes. The prevailing philosophy is that the ability to predict absolute concentration levels well is a necessary condition for predicting concentration changes accurately. We hope that our evaluation study will have resolved the model performance issues before the ROM is used in studies that will influence emissions control policies.

TABLE 3. MAJOR SOURCES OF UNCERTAINTIES IN MODELS LIKE THE ROM

In the model:

(1) Incomplete scientific knowledge
(2) Inexact mathematical descriptions of available knowledge
(3) Errors in empirical data, such as chemical rate constants

In the input data:

(1) Incomplete knowledge of emissions
(2) Inaccurate estimates of emissions, from both anthropogenic and natural sources
(3) Errors and gaps in meteorological data

In the model application:

(1) Limited sample of meteorological scenarios
(2) Stochastic vs. deterministic character of atmospheric phenomena

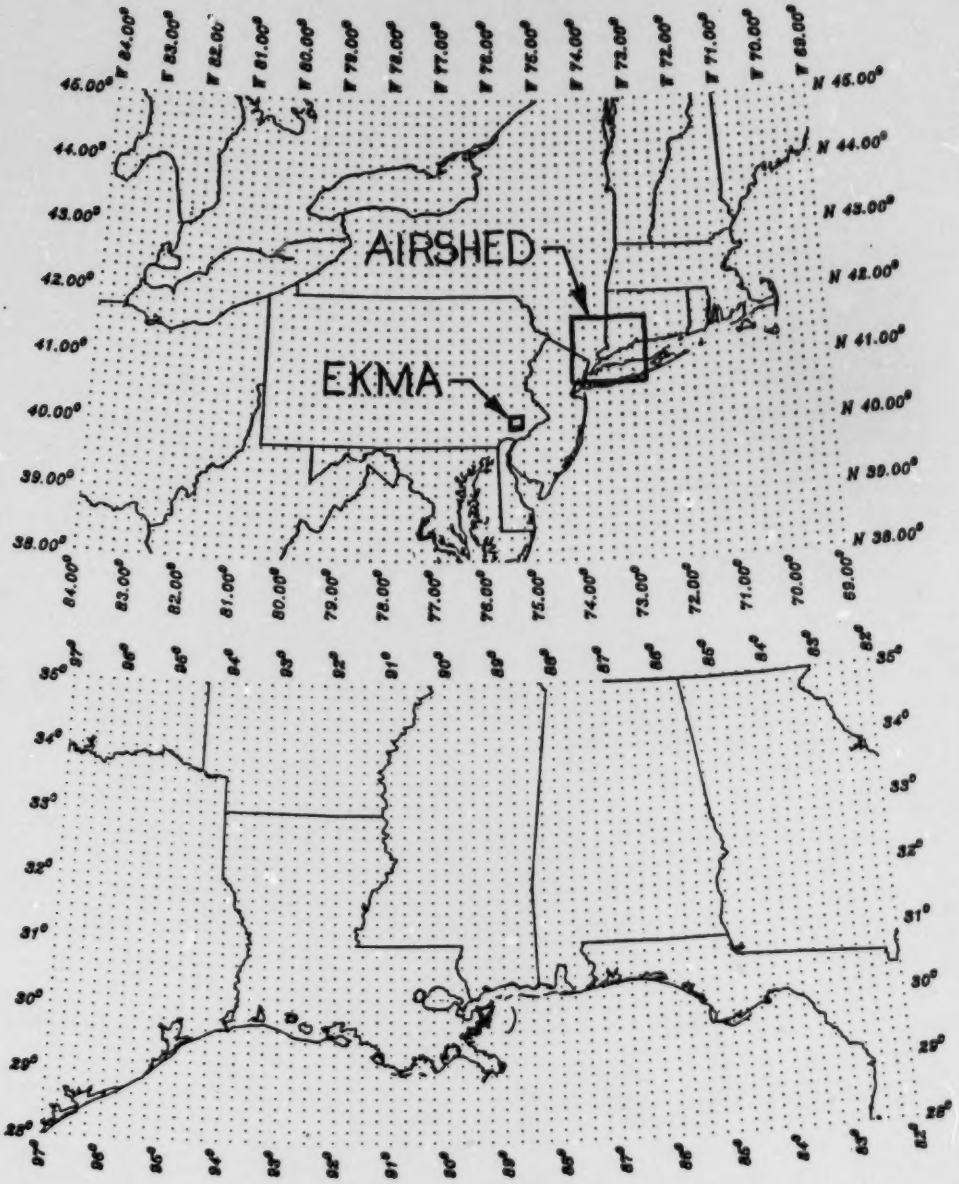

Figure 1. Spatial domains simulated by the Regional Oxidant Model (ROM) in studies of the Northeastern and Southeastern United States. Each dot represents a point at which the model predicts the concentrations of each of 28 chemical species. Boxes labeled "Airshed" and "EKMA" in the upper panel represent typical spatial areas covered by these models.

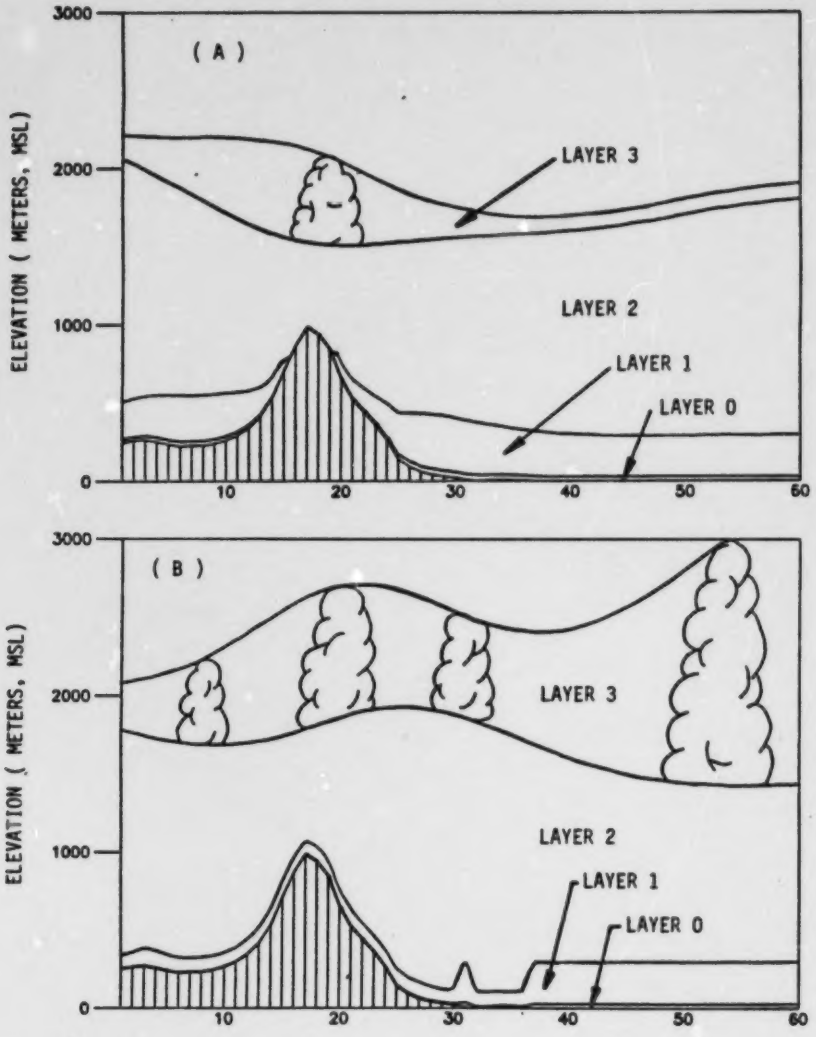

Figure 2. Cross-section through model layers along latitude 38°40' (see Figure 1) at 0700 (a) and 1000 (b) on 18 July 1980. Numbers along abscissa denote grid column.

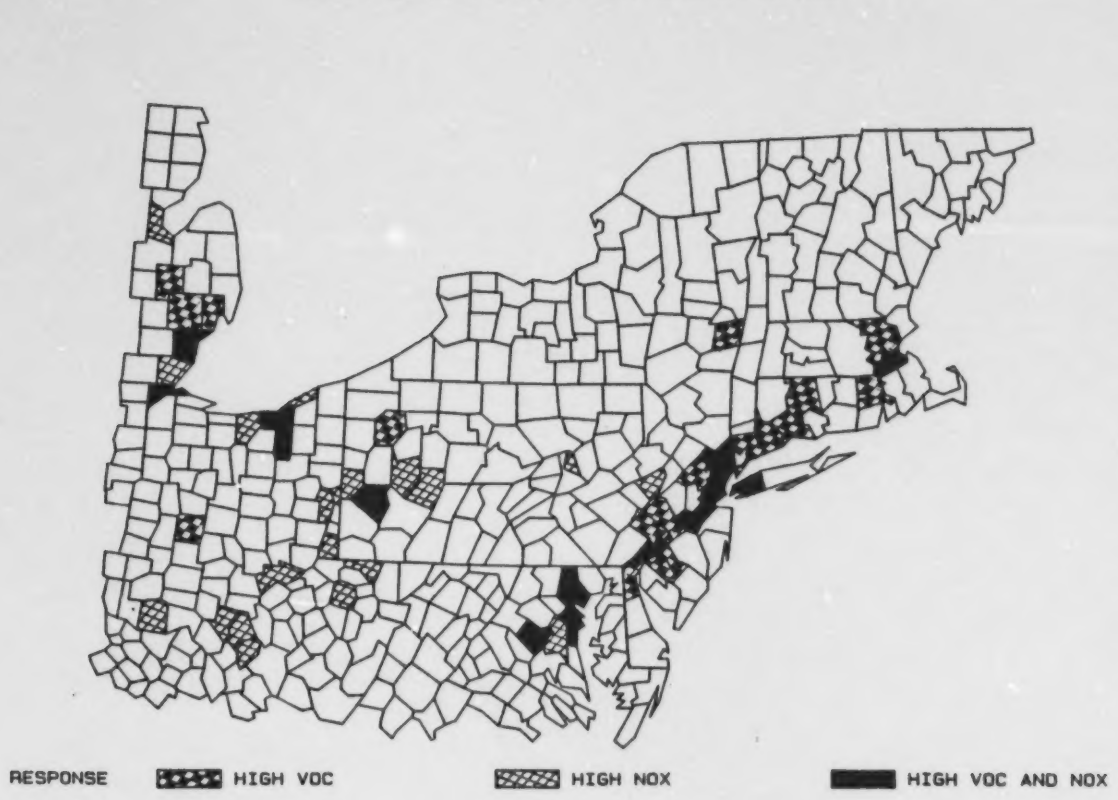

Figure 3. Fifty top county sources of VOC and NO_x based on emissions density Q (moles/area/time). Thirty counties are members of both groups (anthropogenic sources only).

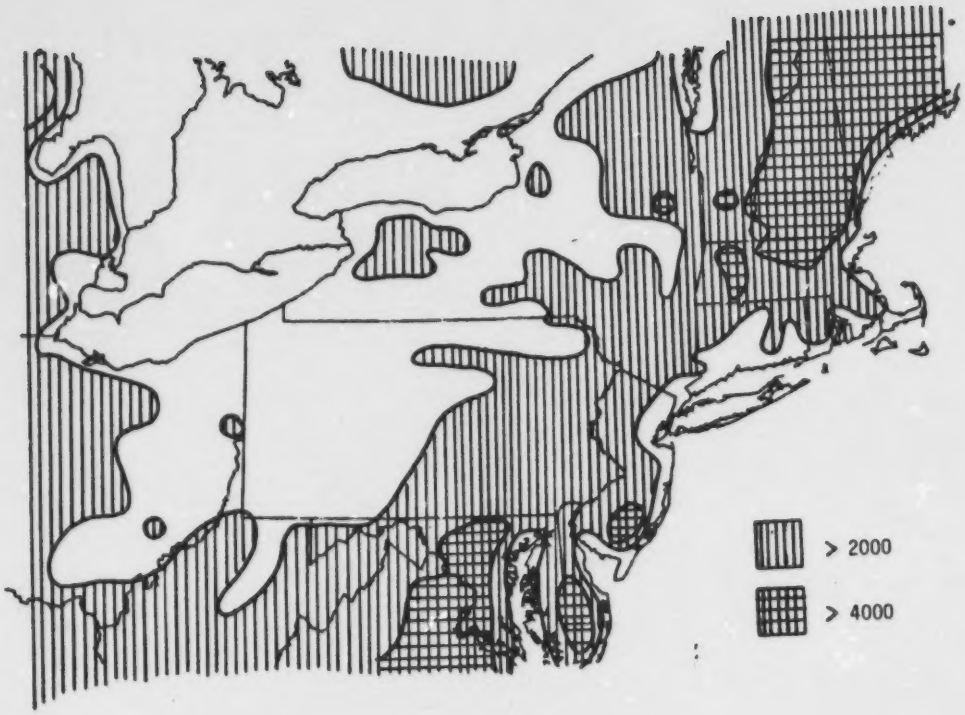

Figure 4. Emission rate (moles/hour/grid cell) of the lumped olefin species OLE from biogenic sources at 1400 EST on Day 196, 1980.

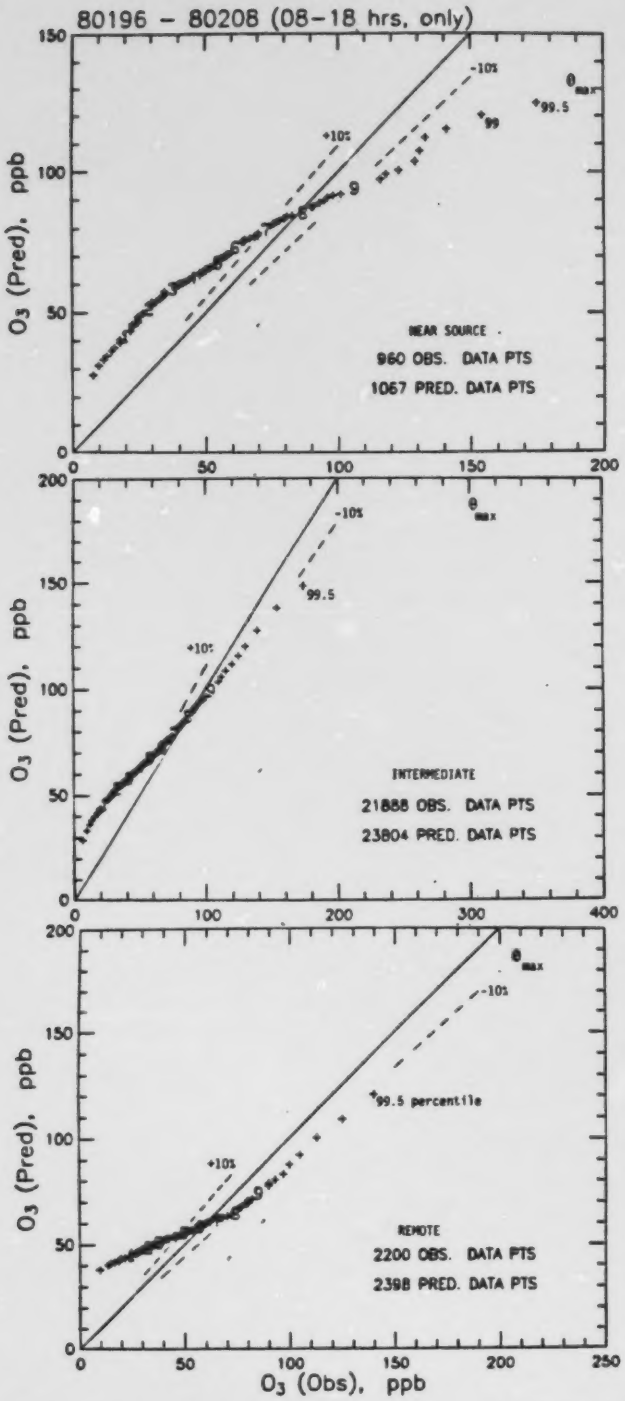

Figure 5 (a):

Comparison of cumulative frequency distributions of observed (abscissa) and predicted (ordinate) hourly O_3 during the period 14-26 July 1980. Solid lines represent perfect agreement; dashed lines mark ±10% discrepancy bounds. Digits mark decile points, e.g., "0" = 100 percentile or maximum value; "9" = 90-th percentile; etc. The symbol "+" marks integer quantile points except where indicated otherwise. Top panel represents receptor sites in the immediate vicinity of major sources. The middle panel represents receptors between about 5 and 150 km of major sources; and the bottom panel represents receptors farther than about 150 km of major sources.

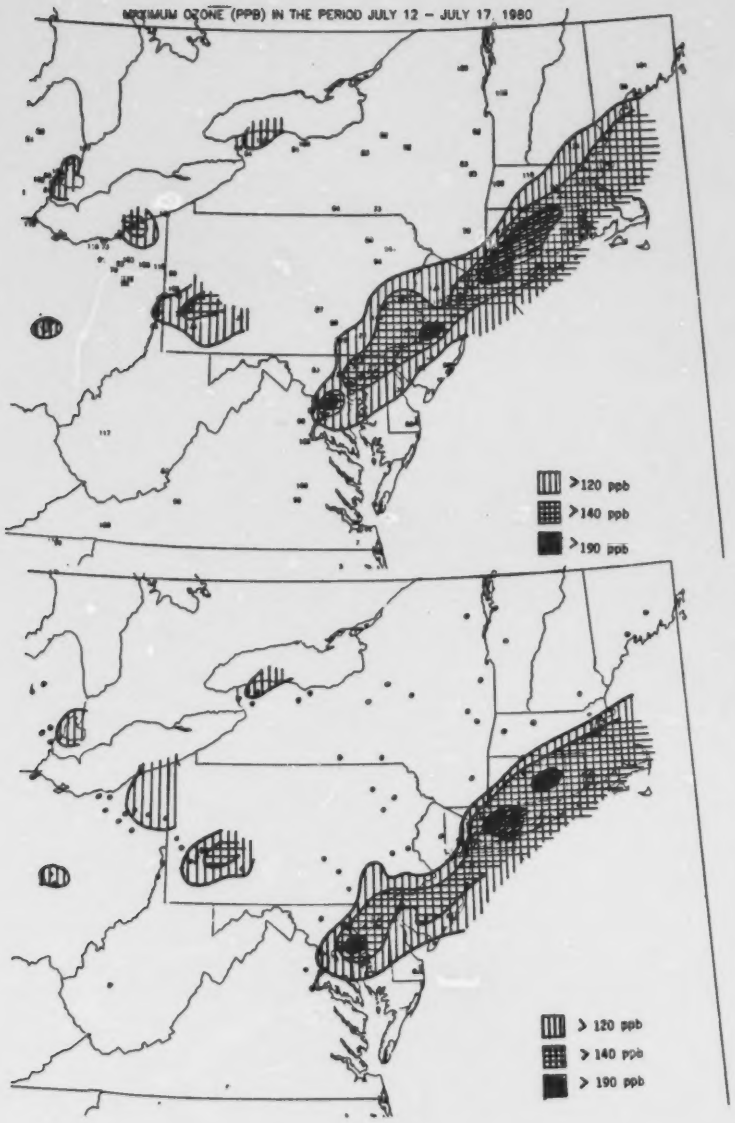

Figure 5 (b) Maximum measured 1-hour averaged ozone concentration at SAROAD sites during the period 12-17 July 1980;
(c) Same as (a) except model predictions replace measured values at SAROAD sites.

SECTION 3

EXTRAPOLATING THE RESULTS OF SIMULATED EMISSIONS CONTROL STRATEGY EFFECTS FROM AN EPISODE TO A SEASON

Air pollution models are used primarily to predict the changes in concentrations that would result from changes in emissions, rather than the absolute concentration levels that would occur from specific emissions. In this respect air pollution models are not used in the same manner as weather forecasting models. This distinction is important not only in the formulation of tests of model performance, but also in the design of methods of extrapolating model results outside the time period simulated. In this Section we consider the theoretical problem of extrapolating concentration changes, or delta concentrations as we shall refer to them, simulated by an episodic model over a period of 3 to 4 weeks to a season consisting of 7 months.

THEORETICAL CONSIDERATIONS

Let A, B, C, etc. denote the concentrations of chemical species A, B, and C in the base case, i.e., the concentration levels predicted by the model during the episode using the uncontrolled source emissions; and let a, b, c, etc. represent the corresponding concentrations predicted using emissions modified in accordance with a specific control strategy. We define the delta concentration to be

$$\Delta A = A - a$$
$$\Delta B = B - b \qquad (1)$$
$$\Delta C = C - c$$
$$\vdots \quad \vdots$$

Similarly, we use S to represent the base emissions, and s to denote the modified emissions. The emissions change is then

$$\Delta S = S - s \qquad (2)$$

The general task is to determine the delta concentrations ΔA, etc. that would result from given emissions changes ΔS in a season given simulated values of ΔA, etc. for only a subset, or episode, within that season. Note that S is used here to represent the emissions of any primary pollutant.

The equations used by the ROM to simulate A, B, etc. have the form (reduced for simplicity)

$$\frac{\partial A}{\partial t} + \frac{\partial}{\partial \zeta} UA - K \frac{\partial^2 A}{\partial \zeta^2} = -k_1 AB + k_2 CD + S_A \qquad (3)$$

where k_1 and k_2 are reaction coefficients; S_A is the base case emission distribution of species A; ζ represents any one of the space coordinates x, y, or z; K is a diffusivity; and U is a wind speed. The equation corresponding to (3) that describes the controlled emissions case is

$$\frac{\partial a}{\partial t} + \frac{\partial}{\partial \zeta} Ua - K \frac{\partial^2 a}{\partial \zeta^2} = -k_1 ab + k_2 cd + s_A \qquad (4)$$

In modeling studies, we solve (3) first and call the results the "base case". Then we solve (4) and the results represent the "controlled case".

The differences in the concentrations are the measure of the effects of the emissions change. Let us examine the relationship between the delta concentrations and delta emissions using Eqs. 3 and 4.

Subtract (4) from (3) and use the definition (from 1)

$$\Delta A = A - a \tag{5}$$

$$\frac{\partial(\Delta A)}{\partial t} + \frac{\partial}{\partial \zeta} U(\Delta A) - K \frac{\partial^2(\Delta A)}{\partial \zeta^2} = -k_1(AB - ab) + k_2(CD - cd) + \Delta S_A \tag{6}$$

Use (5) and its counterparts for ΔB etc. to eliminate a, b, c and d in (6):

$$\frac{\partial(\Delta A)}{\partial t} + \frac{\partial}{\partial \zeta} (U)(\Delta A) - K \frac{\partial^2(\Delta A)}{\partial \zeta^2} = -k_1 B(\Delta A) + k_1(\Delta A)(\Delta B) + [k_2 C \Delta D + k_2 D \Delta C - k_1 A \Delta B - k_2 \Delta D \Delta C] + \Delta S_A \tag{7}$$

If the delta concentrations ΔA, ΔB, etc. are small compared to the corresponding base case values A, B, etc, say $|\Delta A| \leq A/4$, etc., we can ignore the terms in (7) that contain products of delta concentrations. The resulting equation describes ΔA to first order accuracy:

$$\frac{\partial(\Delta A)}{\partial t} + \frac{\partial}{\partial \zeta} (U)(\Delta A) - K \frac{\partial^2(\Delta A)}{\partial \zeta^2} = -k_1 B(\Delta A) + [k_2 C \Delta D + k_2 D \Delta C - k_1 A \Delta B] + \Delta S_A \tag{8}$$

Keeping in mind that the delta concentrations ΔA, ΔB, etc. are the concentration changes that given emissions changes would cause, we observe the following important points on comparing equations (8) and (3):

(1) The emissions change function ΔS acts as the source of the delta concentrations in exactly the same way that the emissions S act as the source of the species concentrations A, B, etc. Note that S, A, B, etc, are never negative; ΔS, and hence ΔA, ΔB, etc, can be positive or negative.

(2) The winds and turbulence transport and diffuse the delta concentrations in exactly the same way that they transport and diffuse the species themselves.

(3) The "chemistry" of the delta concentrations is dominated by interactions of the delta of one reactant with the base concentration of the other reactant, e.g., $B(\Delta A)$, and hence to first order accuracy the chemistry is <u>linear</u>.

THE NATURE OF THE EXTRAPOLATION PROBLEM

The preceeding analysis provides a basis for understanding the problems involved in extrapolating the results of model simulations of emissions controls for short episodes to an entire season. The analysis also provides a basis for developing an approximate extrapolation procedure. First we define basic terms.

Season = 7-month period from the beginning of April to the end of October;

Episode = the period, usually 3 to 4 weeks in length and not necessarily continuous, for which model simulations of emissions controls are performed.

Considering only species A for the purpose of discussion, let $\overline{\Delta A}(\underset{\sim}{x})$ be some average concentration difference or some net benefit of controls

predicted by the model for a given point $\underset{\sim}{x}$ in the episode. Our task is to estimate the value $\overline{\Delta A}(\underset{\sim}{x},t)$ that the model would predict at the same point averaged over the season. Strictly speaking we are not concerned at this point with estimating what the true value of $\overline{\Delta A}(\underset{\sim}{x})$ actually is. This question is related to the issues of model accuracy, predictability, and so on which are not topics of concern in this analysis. The principal objective here is the development of a method of extrapolating model results outside the simulation period irrespective of the accuracy of the model.

The problem of extrapolating simulated delta concentrations outside the model period can be illustrated using the following hypothetical situation. For brevity we consider only a single species because the arguments that apply to one primary species, i.e., those for which S and possibly ΔS are nonzero, apply to all primary species; and the arguments that apply to a secondary species, i.e., those for which S and ΔS are always zero, apply to all secondary species. In the latter case, note that the delta concentrations are generated only by chemical interaction of the base and delta concentrations of the species that produce the secondary pollutant in question (e.g., the term in brackets in Eq. 8).

Consider the situation illustrated in Figure 6 (page 41) in which sources of a hypothetical primary species A exist in three neighboring MSAs (metropolitan statistical areas), labeled MSA's #1, #2 and #3; and consider a control strategy that calls for emissions changes in MSA #1 only. In this case the base emissions distribution S_A has the form shown in Figure 6a and the emission change distribution ΔS_A has the form shown in Figure

6b. We assume that the air quality model has been run for the base case, i.e., using emissions S_A, and for the control strategy, i.e., using $S_A + \Delta S_A$ as the emissions; but that in both cases the simulation was performed for only a brief episode within the season for which the impacts of the emissions changes are desired.

There are three basic problems that obstruct the extrapolation of the model results from the episode simulation to the entire season: (1) differences in the meteorology in the episode and season, (2) differences in the chemistry of the delta concentrations in the episode and season, and (3) differences in the emissions changes ΔS within the season. The last problem is generally not significant because any changes in emissions that are required under a control plan apply equally throughout the year. Consider, then, first the problem created by differences in the meteorology.

As we pointed out earlier, the wind transports and diffuses delta concentration in exactly the same way that it does any chemical species. It follows that if the model were to simulate an inert tracer T emitted only from points where emissions changes are to be made, i.e., the tracer source strength S_T is prescribed as $S_T = |\Delta S_A|$, then delta concentrations ΔA, ΔB, etc., resulting from the emissions change ΔS_A could be nonzero only at points where the predicted tracer concentration T is nonzero. This is simply a consequence of the fact that the chemical species A released by the sources that are to be controlled cannot reach receptors that an inert tracer released by the same source cannot reach, and obviously no changes in the concentration of A or any of the species with which it interacts chemically can occur at sites inaccessible to the emissions of the controlled sources. The problem that this creates in extrapolating

the results of the episode simulation to the season can be illustrated with the aid of Figure 7 (page 42) which shows (hypothetically) the area in which the simulated concentrations of an inert tracer T released from the site of the emissions change ΔS_A shown in Fig. 6b is nonzero during the episode. The shaded area indicates sites where the predicted concentration T is nonzero at least once during the modeling episode.

Consider the two receptor points designated R_1 and R_2 in Figure 7. The model will predict that the proposed emissions changes in MSA #1 have no effect on concentrations of A or B or any other species at R_2 or at any other point outside the shaded area. This result is obviously not applicable to times outside the episode period when the wind direction is such that emissions from MSA #1 pass over receptor R_2. Similarly, the predicted impact of controls on concentrations at R_1 are not applicable to times when the plume from MSA #1 does not pass over R_1. These considerations indicate that if the wind patterns observed during the episode period, and implicit in the shaded area shown in Figure 7, are not representative of the season, extrapolation of the model results to the season will tend to overestimate the effects of controls in the shaded area of Figure 7 and underestimate them everywhere else.

One approach to minimizing this bias in the seasonal extrapolation that seems attractive at first glance would be to express the predicted concentration changes ΔA, ΔB, etc., as a function of the predicted base case concentrations A, B, etc. at the same point, and then use this function and <u>observed</u> values of A, B,... during the season as a means of estimating $\overline{\Delta A}$, $\overline{\Delta B}$,...over the season. The idea here is that the

observed species concentrations are themselves an indicator of the presence of plumes from the major source areas and therefore tying the concentration change ΔA to the observed concentration A would tend to offset any bias introduced by wind direction differences. Another way to look at this is that we would be using the observed concentrations as surrogates of base case model predictions. However, this method is not reliable, especially if the emissions changes ΔS are not applied to all sources equally.

To see this, suppose that the predicted concentration change ΔA at receptor R_1 has been expressed as a function of the predicted base case concentration A at R_1, say

$$\Delta A = f_1(A).$$

Given an observation A_o of the concentration at R_1 at any time in the season, by the method described above we would estimate the corresponding impact of controls to be

$$\Delta A_o = f_1(A_o)$$

where f_1 is the function deduced from the model results. If in the given instance the observed concentration A_o is due to the emissions of MSA #1, then the estimated ΔA value is likely to be accurate; but if the concentration was observed at a time outside the episode when the wind direction was opposite that indicated in Figure 7 and receptor R_1 was within the plumes of MSA #2 and #3, then the estimated ΔA value would be totally incorrect. In this instance the true value would be $\Delta A = 0$ because neither MSA #2 not #3 has emissions controls in this particular strategy. This example demonstrates that the observed concentration alone is not a reliable basis for extrapolating model results of control strategy impacts

from an episode to a season.

The second problem that we noted earlier that complicates the task of extrapolating the model results is differences in the chemistry of the delta concentrations between the episode and season. Referring to Eq. 7 we note that the delta concentrations interact with the base case concentrations A, B, etc. The latter are known only during the episode because they are generated by the model. Consider the example discussed earlier in which the winds during the episode cause emissions from MSA #1 to affect only points within the shaded area shown in Figure 7. At a time in the season when emissions from MSA #1 pass over receptor R_2, the chemistry of the delta concentrations arriving at R_2 is not known because the base case concentrations between MSA #1 and R_2 are not known. In this particular instance, where the base concentrations are due primarily to the emissions of MSA #1, one could reasonably assume that the effects of chemistry on the delta concentrations at R_2 is about the same as that predicted by the model for a receptor within the shaded area at the same travel time downwind of MSA #1. However, at receptors west of MSA #1, it would be possible during northeasterly winds for the base concentrations to be caused partly by MSA #1 and partly by MSA #2 and #3. In these cases no model results would be available on which to estimate the chemistry effects.

From these discussions of the problems created by differences in the meteorology and differences in the chemistry, it appears that the largest extrapolation errors will occur when the receptor in question is influenced

strongly during the season by sources other than those that impacted it during the episode. This suggests that if the estimation of seasonal effects is the principal goal of the model simulations, the episodes should be selected so that they contain at least one sample of each of the meteorological states that cause the major source areas in the vicinity of a given receptor to affect the concentrations that receptor observes.

A PROPOSED EXTRAPOLATION PROCEDURE

To clarify this point and to lay a basis for an extrapolation procedure, we will examine a specific problem based on the hypothetical situation depicted in Figures 6 and 7. First, however, we want to emphasize the point made earlier that the aim of the extrapolation is to estimate what the model would predict were it applied to the entire season. Since, in principle, meteorological conditions and <u>not</u> observed species concentrations are inputs to the model, the extrapolation procedure should be based on meteorological data alone. (Concentration data are required at the lateral and top boundaries of the model only because it is not feasible to simulate the entire atmosphere.) Any use of observed concentrations would be as a surrogate of modeled concentrations, and this would introduce into the extrapolation technique the errors and uncertainties inherent in the model itself. Our position is that the errors associated with the extrapolation technique are distinct from those of the model and therefore the two should be dealt with separately. In this paper we consider the extrapolation problem alone with the understanding that once a scheme is developed, we can then consider its overall accuracy taking into account model errors and uncertainties as well.

To get on with our example, consider the situation shown in Figs. 6 and 7 involving three main source areas MSA #1, #2 and #3. Suppose that we had available three distinct chemically inert tracers T_1, T_2 and T_3; and suppose that T_1 were released steadily from MSA #1 over the entire season, and that T_2 and T_3 were released in the same manner from MSA #2 and #3, respectively. Suppose next that model simulations of the dispersion of these tracers were performed for the entire season using actual meteorological data. We add that a simulation of this type is feasible because the execution speed of the model is about 10 to 20 times faster for chemically inert species than it is for photochemical pollutants. Thus, the model can simulate 180 days of inert tracer concentrations in about the same time that it needs to simulate 21 days of ozone concentrations.

For any receptor site $\underset{\sim}{x}$ in the model domain and any hour t in the season we define a binary number $B(\underset{\sim}{x},t) = (b_1, b_2, b_3)$ whose elements b_n are binary numbers defined as follows:

$$b_n = \begin{cases} 1 & \text{if the concentration of } T_n \text{ at } (\underset{\sim}{x},t) \text{ is nonzero;} \\ 0 & \text{otherwise.} \end{cases} \qquad (9)$$

Thus, $B(\underset{\sim}{x},t) = 010$ if $T_1 = T_3 = 0$, $T_2 \neq 0$ at $(\underset{\sim}{x},t)$;

$= 000$ if $T_1 = T_2 = T_3 = 0$ at $(\underset{\sim}{x},t)$;

$= 111$ if $T_1, T_2, T_3 \neq 0$ at $(\underset{\sim}{x},t)$; etc.

Keep in mind that the function B is derived from the output of the model produced by a simulation of the three inert tracer sources over the entire season. (In practice we would use some small concentration level ε as the threshold for setting $b_n = 1$, rather than $T_n = 0$, because model noise affects concentration values near the zero level.)

Consider now receptor site R_2 in Figure 7 at which we are interested in extrapolating the results of simulated control strategy effects from an episode to the full season. The influence of the three MSAs on concentrations at R_2 over the season can be summarized in the form of a Karnaugh table as shown in Table 4.

TABLE 4. REPRESENTATION OF THE FUNCTION B EVALUATED AT RECEPTOR R_2 IN FIGURE 7, INTEGRATED OVER THE SEASON. NUMBERS INDICATE THE PERCENTAGE OF HOURS IN THE SEASON WHEN $B(x = R_2,t)$ HAD THE VALUE INDICATED. A DASH (-) IN THE TABLE INDICATES LESS THAN 1 PERCENT OCCURRENCE OF THAT VALUE

b_1 \ b_2b_3	00	01	11	10
0	55	-	15	4
1	24	-	2	-

Here we are using the Karnaugh table (which is borrowed from logic analysis) as a basis for expressing the potential influence that each major source and combinations of major sources can have on a given receptor. The numbers in Table 4 are the percentages of time in the season that the function B, as determined by the model predictions, had the value specified by the row and column coordinates. In order to display B, which has three elements b_1, b_2 and b_3, on a 2-D chart, element b_1 is split out to form the row entry to the table and the pair b_2b_3 make up the column entry. Thus, the number 55 in the upper left corner of Table 4 indicates that during 55% of the season all three tracers T_1, T_2 and T_3 were simultaneously absent at R_2, i.e., $b_1b_2b_3 = 000$. The number 24 just below the 55 indicates that 24% of the season, T_1 was predicted at R_2 but at those times neither T_2 nor T_3

was present (B = 100). Similarly, T_2 and T_3 were present at R_2 with T_1 absent (011) 15% of the time; T_2 was present with T_1 and T_3 absent (010) 4% of the time; and on 2% of the hours in the season all three tracers were predicted at R_2 simultaneously. The total of the entries in the table is 100 percent. We can construct tables like this for any number of sources, although for numbers larger than n = 8 the tables become quite unwieldy. Note that the number of elements, or slots, in a table is 2^n, where n is the total number of source areas represented.

In the analyses that follow we will distinguish between the elements of a table and the entries in a table. The former is defined as the intersections of the rows and columns of a table while the entries are defined as the percentage values written at the locations of each element. For example, Table 4 has 8 elements but only 5 entries. We now define the dominant entries of a table as follows. Let the entries be arranged in rank order from highest value to lowest. The dominant entries are the first M members of the rank ordered set where M is the number such that the sum of the first M entries is closer to some limit, say 90 (percent), than the sum of the first M-1 or M+1 entries.

Using the example shown in Table 4 as an illustration, the rank ordered entries are 55, 24, 15, 4, 2. The sum of the first three of these is 94 which is closer to 90 than the sum of the first two (55+24 = 79) or the first four. Hence, 55, 24 and 15 are the dominant entries.

We define the dominant elements of the table to be the elements associated with each dominant entry, and we indicate the dominant elements by checks in a dominant element table. Table 5 shows the dominant elements corresponding to Table 4.

TABLE 5. DOMINANT ELEMENTS, INDICATED BY CHECKS (✓), OF THE KARNAUGH TABLE, TABLE 4, FOR RECEPTOR R_2 (SEE FIGURE 7)

b_1 \ b_2b_3	00	01	11	10
0	✓		✓	
1	✓			

The Karnaugh tables that we have discussed up to this point were compiled using the inert tracer concentrations simulated by the model for the entire season of interest. Thus, we will refer to these as seasonal tables and to their elements as $B = (b_1b_2b_3)$. By applying the same procedures to any subset of the simulated tracer concentrations over the season, we can produce episode tables. We will refer to the elements of an episode table as $B' = (b_1'b_2'b_3')$. We emphasize that the subset of the season that is used as the episode does not have to be continuous in time. One can select one time interval at one point in the season and intervals of different lengths at different times and treat the combined set as a single subset or episode. We also want to emphasize that the seasonal and episode tables pertain to specific receptor sites, and in general the entries in either table will vary from receptor to receptor.

Recalling the earlier discussion of the effects of meteorology and chemistry on extrapolating the results of control strategy simulations from an episode to a season, we now advance the following hypothesis:

> The simulated effects of emissions controls can be extrapolated from an episode to a season for any receptor site whose episode table covers its seasonal table. (H1)

We say that Table A covers Table B if all dominant elements of B are also dominant elements of A. Thus, in simple terms hypothesis H1 states that the extrapolation process is possible if the dominant element table of the episode contains a check (✓) in every box that the seasonal table has one. The episode table may contain more checks (dominant elements) than the seasonal table, but this is not necessary to achieve coverage.

As an example, consider receptor R_2 shown in Figure 7. The seasonal table for this receptor is given in Table 4 and its dominant elements are shown in Table 5. We assumed earlier that model simulations have been performed for an episode in this season, and that model simulations of an inert tracer T_1 released steadily from MSA #1 predict nonzero tracer concentrations only within the shaded portion of Figure 7 over the time period covered by the episode. This result suggests that the episode table for receptor R_2 is as shown in Table 6. In this instance none of the three source areas influences receptor R_2 at any time during this specific episode.

TABLE 6. THE EPISODE TABLE (a) AND ITS DOMINANT ELEMENTS (b) FOR RECEPTOR R_2 AND THE EPISODE SHOWN IN FIGURE 2

(a)

b_1 \ b_2b_3	00	01	11	10
0	100	-	-	-
1	-	-	-	-

(b)

b_1 \ b_2b_3	00	01	11	10
0	✓			
1				

On comparing Table 6b with Table 5 we see that the dominant elements of this episode do not cover those of the season. The latter contains dominant elements with coordinates $(b_1b_2b_3) = (011)$ and (100) that are not present in the episode. Thus, according to our hypothesis this episode is not a good basis for estimating the seasonal effects of controls on concentrations at R_2. Before we consider methods of dealing with deficiencies of this kind, let us first describe how the seasonal effects are estimated once an adequate episode has been established.

Suppose that we have found an episode whose dominant elements cover those of the season shown in Table 5. Since there is a unique value of $B' = (b_1'b_2'b_3')$ at R_2 for each hour of the episode (cf Eq.9), we can identify all those hours in the episode associated with each of the three dominant elements $(b_1'b_2'b_3') = (000)$, (011), and (100). Let E_{000} be the predicted total benefit of emissions controls at R_2 for all hours associated with (000) in the episode, and let E_{011} and E_{100} be the corresponding benefits predicted for all hours associated with (011) and (100), respectively. The benefit might be the average delta concentration, e.g.,

$$E_{011} = \frac{1}{K} \sum_k \Delta A(\underset{\sim}{x} = R_2, t_k) \tag{10}$$

where the summation is over all K hours t_k in the episode for which $(b_1'b_2'b_3') = 011$, and ΔA is the predicted change in the concentration of a particular species; or the benefit might be some dollar value of crop yields. In any event, the corresponding benefit $\bar{E}$ at R_2 for the season is extrapolated to be

$$\bar{E}(R_2) = e_{000}E_{000} + e_{011}E_{011} + e_{100}E_{100} \tag{11}$$

where e_{000} is the percentage occurrence of $(b_1b_2b_3) = (000)$ in the

season, as given in the present example by the entries in Table 4 (e_{000} = .55). Similar meanings apply to e_{011} and e_{100}(e_{100} = .24, e_{011} = .15).

This is the essence of the proposed extrapolation technique. Up to this point we have not considered differences in sun angle, wind speed, mixing depth or other meteorological parameters that affect concentrations. In principle, these can be taken into account in the proposed extrapolation scheme by dividing each of the states B and B' in the Karnaugh tables into substates representing different combinations of wind speed, mixing depth, etc. We plan to add this feature as we develop advanced implementation of the extrapolation scheme.

Next we consider ways of getting the episode table to cover the seasonal table.

APPLICATION OF THE EXTRAPOLATION PROCEDURE

In practice we usually do not have the luxury of being able to change the modeling episode at will. Often the episode has already been selected and modeled, and our task is to extrapolate the results of that simulation to the season for any or all receptor sites in the model domain. In general we will find that the episode table does not cover the seasonal table at every receptor. At those locations we can attempt to achieve coverage by one of two methods: (1) we can ascertain whether those dominant elements in the seasonal table that are not covered by elements in the episode table are irrelevant insofar as the evaluation of the control strategy of interest is concerned, and therefore are "removable"

elements; or (2) we can attempt to "fill in" necessary elements in the episode table by borrowing from the episode tables of other receptors. We will call the first method "reducing the seasonal table" and the second method "filling in the episode table". These are described below.

Reducing the Seasonal Table

The earlier analysis of the dependence of the delta concentrations ΔA, etc. on the delta emissions ΔS leads naturally to the following proposition:

> Insofar as the evaluation of a specific control strategy is concerned, any dominant element in the seasonal table whose coordinate $(b_1 b_2 \ldots b_n)$ contains zeros at all positions b_m, $m < n$, representing sources that are controlled in that strategy can be removed. (P1)

A corollary to this proposition is that the dominant element $(b_1 b_2 \ldots b_n) = (00\ldots0)$ is always removable. This is a consequence of the fact that this particular element represents all hours when the receptor in question is not influenced by any of the major sources, so naturally at all these times the benefits of controls are zero ($E_{00\ldots0} = 0$ in (11)). This result is true only if the sources represented in the seasonal table are the only controlled sources. If, for example, widely distributed minor sources that are not represented in the tables are subjected to the same controls as the major sources, the benefit $E_{00\ldots0}$ can possibly be nonzero as a result of the minor source controls. As a result the seasonal impact may be significant if $e_{00\ldots0}$ is large. This point should be taken into consideration when sources are identified for inclusion in the seasonal table calculations.

To give an example of reducing a seasonal table, consider the table of receptor R_2 given in Table 5 (page 33). In our earlier examples we

considered a control strategy in which only the emissions of source 1 (MSA #1, in Figures 6 and 7) were to be controlled. According to proposition P1 above, for the purposes of evaluating this strategy we can remove, i.e., ignore, any dominant element in Table 5 whose coordinates $(b_1b_2b_3)$ have a zero in the position representing source 1, namely b_1. In this case this is the entire top row of the table, so dominant elements (000) and (011) in Table 5 are removable. Thus, for this particular control strategy evaluation it is only necessary to cover the reduced seasonal table shown in Table 7. Comparing this table with the episode table for receptor R_2 shown in Fig. 6b, we see that even the reduced table is not covered. We need to fill in the episode table with model results for state $(b_1b_2b_3) = (100)$.

TABLE 7. REDUCED SEASONAL TABLE FOR RECEPTOR R_2 APPLICABLE TO SEASONAL EXTRAPOLATION OF MODEL RESULTS OF A CONTROL STRATEGY IN WHICH ONLY THE EMISSIONS OF SOURCE 1 (MSA #1) ARE CHANGED

b_1 \ b_2b_3	00	01	11	10
0				
1	✓			

Filling in The Episode Table

"Filling in" the episode table means acquiring model results for the conditions represented by the state $(b_1b_2...b_n)$ whose table entry is missing. In the particular example at hand, we want to fill in element $(b_1b_2b_3) = (100)$ in the episode Table 6b so that it covers the seasonal

Table 7. This means that we need results of the control strategy simulation at receptor R_2 for hours when emissions from MSA #1, but not MSAs #2 or 3, are affecting this receptor, i.e., state (100); but according to the episode table (6b) these results are not available because emissions from MSA #1 never reach receptor R_2 at any time during this particular episode.

To approximate the needed information, we look first at receptor R_1 in Fig. 7. Judging from the area influenced by emissions of MSA #1 during the episode as indicated by the shading in Fig. 7, we deduce that the episode table of R_1 would have the form shown in Table 8. At this receptor, model results are available for state $(b_1b_2b_3) = (100)$. Since receptor R_1 is roughly the same distance from MSA #1 as receptor R_2, we propose to fill in the data needed at (100) in the episode table of R_2 with the corresponding data of the table of R_1. That is, we assume that the model results that we need to extrapolate seasonal benefits at R_2 are approximately the same as those that are available at receptor R_1. Thus, we arrive at the following estimate of seasonal benefits at R_2:

$$\bar{E}(R_2) = e_{100}E_{100}(R_1) \tag{12}$$

where e_{100} is the percentage occurrence of state (100) in the season (= .24), and $E_{100}(R_1)$ is the model simulated benefit of controls at receptor R_1 during the state (100) of the episode.

TABLE 8. DOMINANT ELEMENTS OF THE EPISODE TABLE OF RECEPTOR R_1 SHOWN IN FIGURE 7

b_1 \ $b_2 b_3$	00	01	11	10
0	✓			
1	✓			

This is the essence of the technique of filling in episode tables by borrowing results from neighboring receptors with similar characteristics.

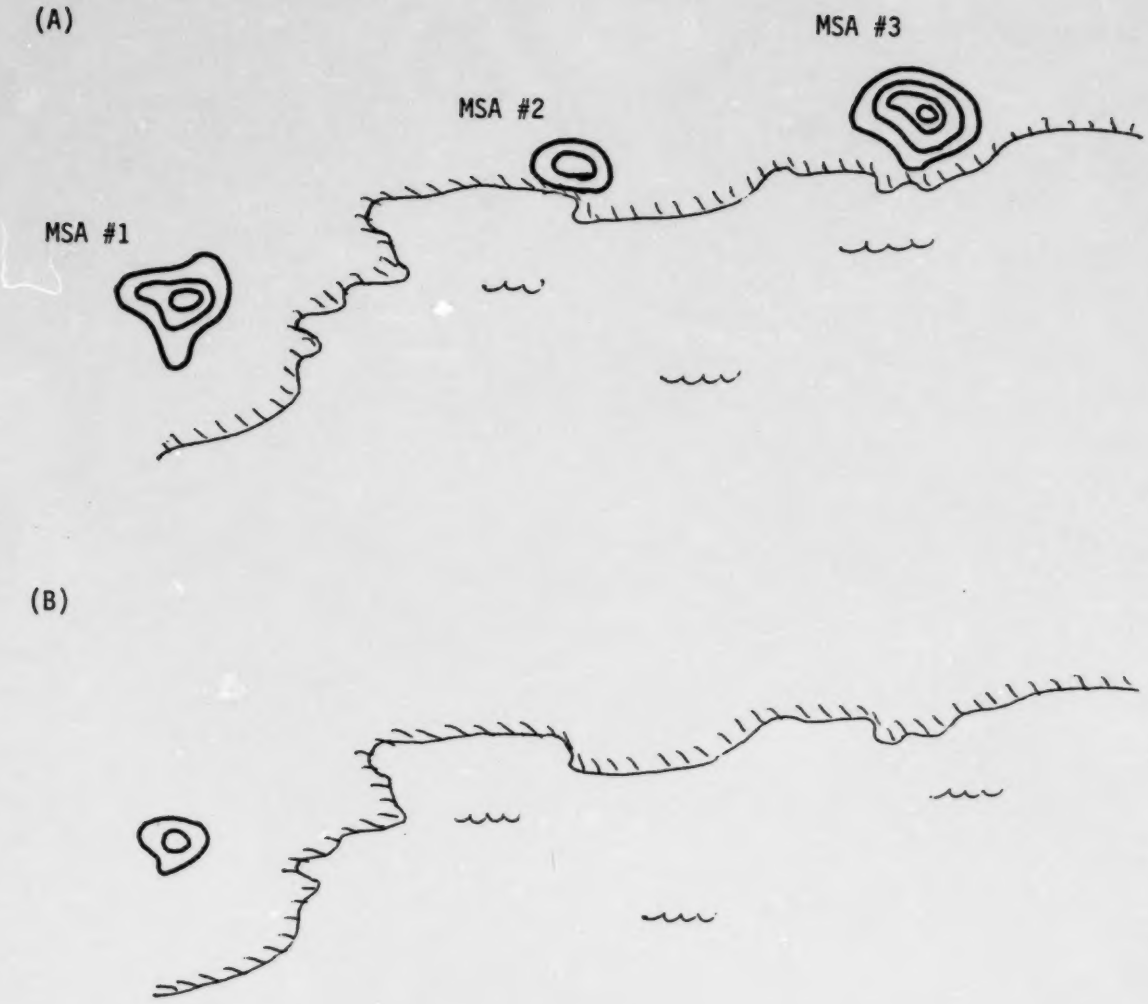

Figure 6(a). Isopleths of the emissions S_A of three hypothetical metropolitan statistical areas (MSAs).
(b). Isopleths of the emissions change distribution ΔS_A describing a control strategy in which emissions controls would be implemented in MSA #1 only.

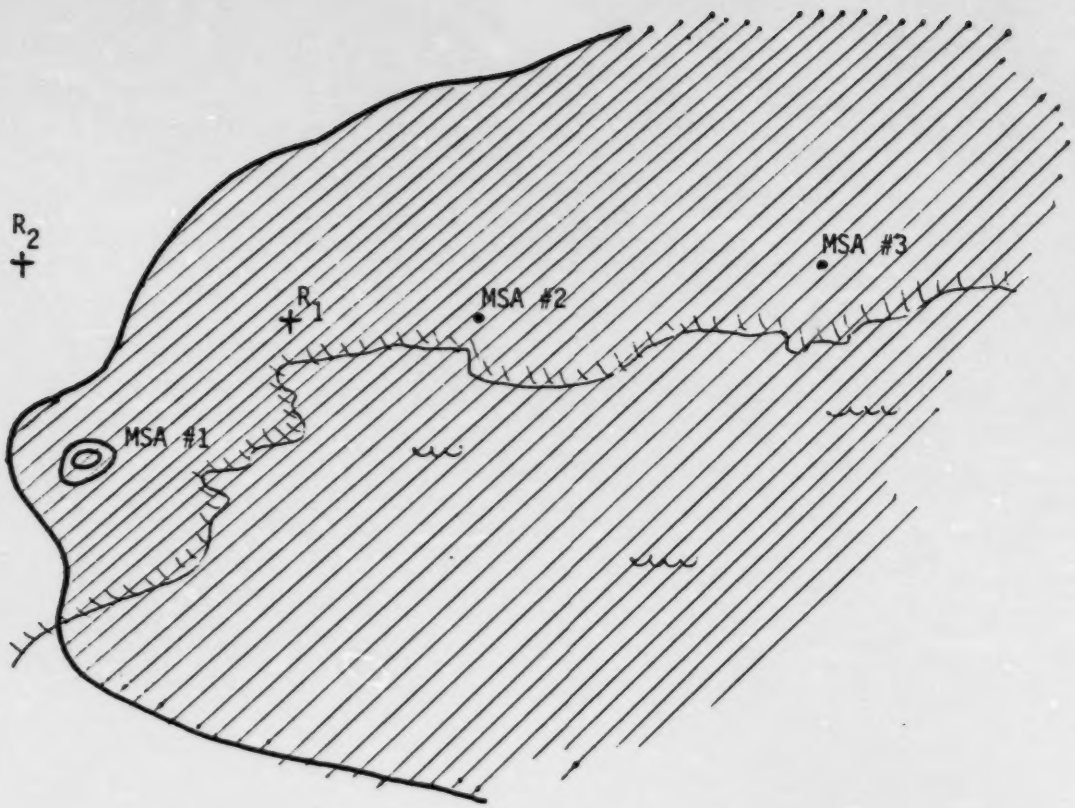

Figure 7. Area (hatched) in which the simulated concentration of an inert tracer T emitted within MSA #1 at the locations of proposed emissions changes (see Fig. 6b) is nonzero for at least one hour during the episode period. R_1 and R_2 indicate receptor points discussed in the text.

SECTION 4

INTERIM IMPLEMENTATION OF THE EXTRAPOLATION SCHEME

A rigorous implementation of the seasonal extrapolation method just described would require that the ROM generate the inert tracer concentration fields, used to define the states B, for the entire season. This is not possible at the present time, so we present here an interim implementation of the scheme that utilizes the ATAD trajectory model (see Hefter, et al 19). We also adopt several strong assumptions to simplify the analysis. These include the neglect of vertical wind shear, vertical turbulent diffusion, and vertical air motion including the vertical motion associated with convective clouds. We also resolve the spatial and temporal variations in the tracer concentration fields with limited resolution. We treat blocks of 5x5 ROM cells as single "receptors" -- this has the effect of smoothing the tracer concentrations over roughly 100 km subdomains -- and tracer concentrations are sampled every 6 hours rather than every 30 minutes as the ROM would provide.

In order to minimize the data handling requirements of the interim scheme, we consider only 27 source sites. These are shown in Figure 8 (page 52). These particular sites were selected because they are the locations where the largest absolute reductions in VOC would occur under the control strategy identified as #1 in the rural ozone studies (to be described further in the next Section). Beginning at hour 0000 Z on 1 April, and at every subsequent six-hour interval 0006, 0012, etc, until 2400 Z 31 October, a particle is released from each of the 27 source

sites and tracked by the ATAD model for a period of 5 days, or until it passes outside the model domain. Every six hours a count is made of the particles in each receptor. These consist of the 98 rectangular cells arranged in the 12x9 array shown in Fig. 8. The receptors are identified by their column and row coordinates, (I,J), where $1 \leq I \leq 12$, $1 \leq J \leq 9$. When the particle counts are performed, a separate running tally is maintained for each of the 27 sources. At the end of the season, the source with the highest total count at a given receptor is the source that affects that receptor most frequently. The source with the next highest count is the second most significant source, and so on. In this way we identify for each receptor (I,J) the eight most significant sources. This information is then used to define the state variable

$$B(I,J,t_n) = b_8b_7b_6b_5b_4b_3b_2b_1$$

described earlier. Recall that the b_k are binary numbers with $b_k = 1$ if at time t_n, where t_n is any hour in the season, tracer material is present at receptor (I,J) from the k-th significant source. Otherwise, $b_k = 0$. For example, if at a given time tracer is present from the most significant source (k=1) simultaneously with material from the second and eight most significant sources, then $B(I,J,t_n) = 10000011$. If there were no tracer material present at t_n from any of the top eight sources, $B(I,J,t_n) = 00000000$.

Note the following important aspects of B: (1) it is a discrete valued function with $2^8 = 256$ possible values; (2) the specific sources (of the set of 27) represented by each b_k may differ from one receptor to another; (3) the most significant source is represented by the rightmost

bit of B while the the 8-th most significant source is represented by the leftmost bit; and (4) at each receptor there is a unique value of B associated with each hour of the year.

As we noted earlier the ozone season is currently defined as 1 April through 31 October. In the present study the episode consists of the following three disconnected periods: 14-29 April, 12-26 July, 20-31 August. Table 9 (page 46) contains the seasonal/episode state tables for two receptors, (I,J) = (8,6) and (8,7), computed by the procedure described above using meteorological data for 1980. The column entry of each table is the rightmost four bits of B(I,J), i.e., $b_4b_3b_2b_1$ which represent the four most significant sources at receptor (I,J); and the row entry of each table is the leftmost four bits, $b_8b_7b_6b_5$. The specific sources represented by each bit are shown just above the column and row headings. (Refer to Figure 8, page 52, for the source locations.)

Each table has three types of entries: (1) two numbers separated by a colon, (2) a single number, or (3) a blank. A blank signifies that the state B represented by that particular column/row entry in the table did not occur in the season, nor the episode. A single number signifies that the state occurred in the season but not the episode. In this case the integer shown is the number of occurrences, in units of quarter days (6 hours), of that state in the season. Finally, an entry of the form n:m indicates the number of occurrences of the state found in the season (m) and the episode (n). The state tables provide an easy means of assessing how well the chosen episode represents the season, at least insofar as the source impacts are concerned.

TABLE 9. SAMPLE EPISODE/SEASONAL STATE TABLE FOR TWO RECEPTOR SITES (I,J) SHOWN IN FIGURE 8 (PAGE 52). SEE TEXT FOR EXPLANATIONS OF THE TABLE ENTRIES

SEASONAL AND EPISODE KARHAU TABLE FOR RECEPTOR (I= 8 J= 6)
SEASON=(1 APRIL-31 OCTOBER 1980) EPISODE=(12-26 JULY, 20-31 AUGUST, 14-29 APRIL, 1980)
SEASON SUM= 856 EPISODE SUM= 159

ROW LABEL (1,1,1,1) COLUMN LABEL (1,1,1,1)REPRESENTS SOURCES(10,17,12,16)
REPRESENTS SOURCES
(11, 5, 8, 7)

/	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0000	87:435	19:102	3:33	3:19	6:43	1	1		2:25	2:10	7	4:19	1:3			
0001	2:13	2			2:7				1:2		2					
0010	4:13				1:5						1	1				
0011	3	2			2											
0100	5:19	3:5	1:1		1				1:2		1:2	1				
0101	1:5				1:3				1	1						
0110	1				1	1										
0111	1	1:1		1				1:1	1							
1000	3:20				1:5			1:1					1		1	1
1001	1:3															1
1010	1:6				3				1		1		1			
1011	1				1	1										
1100	2															
1101	1															
1110	1															
1111	1											1:1	1			1

SEASONAL AND EPISODE KARHAU TABLE FOR RECEPTOR (I= 8 J= 7)
SEASON=(1 APRIL-31 OCTOBER 1980) EPISODE=(12-26 JULY, 20-31 AUGUST, 14-29 APRIL, 1980)
SEASON SUM= 856 EPISODE SUM= 159

ROW LABEL (1,1,1,1) COLUMN LABEL (1,1,1,1)REPRESENTS SOURCES(7,10,12,16)
REPRESENTS SOURCES
(2,17, 5, 9)

/	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0000	95:500	6:66	1:26	5:20	3:21	7:18	3:10	10	3:14	1:3	2:5	2			1	
0001	4:27	1:5	1:4	3	2	1:2	3:5	2:2								
0010	1:4	3:4			1	1			1:6	3	2	1	2			
0011	1:1						1	1								
0100	1:24	1:2	2	1					1					1		
0101			1				1:2									
0110	4								2							
0111																
1000	3:8	1:3	1	1	3	1	1		1							
1001	1:4				1:2											
1010	1:1	1							3	1:2	1					
1011							1							1		
1100	1															1:1
1101																
1110									1			1:1				1:1
1111													1:1		1	1

Since there is a unique value of B associated with each hour, regardless of whether the hour is inside or outside the episode, for extrapolation purposes we can equate unmodeled hours in the season to modeled hours in the episode using the B values as the basis. Another way of saying this is that for any receptor (I,J) we can map the simulated effects of emissions controls at a given hour t_n of the episode into any hour t_m of the season as long as $B(I,J,t_n) = B(I,J,t_m)$. Table 10 (page 48) shows the mapping for the first 12 days of the season at 12 receptors (I,J), $1 \leq I \leq 12$, $J = 2$, derived from the interim implementation of the extrapolation scheme that we have described to this point.

The second column from the left contains 5 digit numbers of the form DDDHH where DDD is the Julian date in the season (1980), and HH is the ending hour (EST) of a 6-hour block. Columns 3-14 contains the corresponding day and hour in the episode from which model results can be used to estimate benefits at time DDDHH at the receptor identified at the top of the column. The mapping relationships shown in Table 10 were generated under the following constraints:

(1) The 6-hour morning period ending at 1300 EST can be extrapolated only from 6-hour morning periods in the episode.

(2) The 6-hour afternoon period ending at 1900 EST can be extrapolated only from 6-hour afternoon periods in the epiosode.

(3) The nighttime period 1900-0700 can be extrapolated only from nighttime periods in the episode.

These constraints help maintain accurate diurnal variations in concentration patterns. To help maintain realistic temporal variations over multiple days, the episode states ($B(I,J,t_n)$ are examined sequentially in forward

TABLE 10. EPISODE-TO-SEASON EXTRAPOLATION MATRIX FOR THE 12 RECEPTORS INDICATED BY THE COLUMN HEADINGS FOR THE FIRST 12 DAYS OF THE SEASON. SEE TEXT FOR FURTHER EXPLANATION

		MAPPING FACTORS FOR RECEPTOR (I,J):											
ICLE=	TIME=(DDDHH) DDD=JULIAN DATE HH=6-HOUR PERIOD (EST) ENDING	(1,2)	(2,2)	(3,2)	(4,2)	(5,2)	(6,2)	(7,2)	(8,2)	(9,2)	(10,2)	(11,2)	(12,2)
1	9201	10601	11207	10607	10601	10601	12001	0	10601	10601	10601	10601	10601
2	9207	10607	11401	11607	19601	11707	19601	0	10607	10607	10607	10607	10607
3	9213	10613	11413	20513	20113	19513	20613	23613	10613	10613	10613	10613	10613
4	9219	10619	11419	23319	24119	19519	23819	23419	10619	10619	10619	10619	10619
5	9301	10701	11601	23401	24201	19707	0	19607	10801	10701	10701	10701	10701
6	9307	10707	11607	23801	24207	20107	24107	0	10901	11001	10807	10707	10707
7	9313	10713	11813	23813	11113	20213	24313	19813	11313	11013	10813	10813	10813
8	9319	10719	19419	24219	11519	24119	11119	19919	0	20719	0	11019	10819
9	9401	10801	19801	23601	11607	10707	11701	20701	0	20807	11107	0	0
10	9407	11001	20807	0	0	0	12001	23407	19601	23401	19507	11101	11007
11	9413	11013	0	0	0	11413	23413	23713	19613	23913	19513	11113	0
12	9419	11119	23319	23719	19419	11919	0	23519	11319	19619	19519	11319	19619
13	9501	11201	23401	23801	19501	12001	23507	24301	11401	19801	20807	11401	19701
14	9507	11301	23407	23807	19507	19501	23601	24307	11601	19807	23401	11507	19707
15	9513	11413	23413	23813	20113	19613	24013	24313	11613	19913	23413	11513	19713
16	9519	11419	0	24219	20119	19619	24119	24319	11619	19919	23419	11519	19719
17	9601	11501	23907	24301	23401	19701	24401	24401	11707	20007	23501	0	19801
18	9607	11601	24001	10707	23701	19801	10707	10601	0	10707	0	19907	19807
19	9613	11613	24013	10713	23813	11713	10713	10613	11013	11013	19813	0	24013
20	9619	11619	24019	11119	23819	0	10719	10719	11819	11019	0	19619	24119
21	9701	11701	24101	11407	23901	12001	10801	11101	0	19707	19507	19701	24201
22	9707	12001	24107	12007	11607	19501	20601	11107	10907	24001	11001	19707	24207
23	9713	19613	24113	20013	11613	19613	20713	0	10913	0	0	0	24213
24	9719	19719	24119	20219	11619	11619	0	24119	0	10719	0	19719	19619
25	9801	19801	24301	20301	19501	20107	24301	20501	0	10907	0	10901	19701
26	9807	19807	24307	20307	19507	20201	24401	20801	20107	0	24007	11301	19707
27	9813	19813	24313	20313	20113	20213	10613	24313	20113	11013	0	11413	19713
28	9819	19819	24319	20419	20119	20219	10619	24319	20319	11019	24219	11419	19719
29	9901	19901	24401	23801	20201	20301	10701	24401	20401	11101	24301	11507	19801
30	9907	19907	10607	23807	20207	20307	10801	10601	20407	11201	24307	11601	19807
31	9913	19913	10613	23813	20213	20313	10913	10613	20413	11513	24313	11613	19813
32	9919	19919	10619	24219	20219	20319	11019	10619	20419	11619	24319	11619	19819
33	10001	20001	10701	24301	20301	20407	11107	10701	20501	11701	24401	11701	19901
34	10007	20007	10707	24307	20307	20501	11301	10707	20507	11707	10601	11707	19907
35	10013	20013	10713	24313	20314	20713	19713	11113	20513	11713	10613	11713	19913
36	10019	20019	10919	24319	20419	23419	19819	11819	20519	11819	10619	11719	19919
37	10101	20101	11107	24401	20501	23501	19907	11901	20807	11901	10701	11801	20001
38	10107	20107	11201	10607	20807	23507	20107	11907	23407	11907	10807	11807	20007
39	10113	20113	11313	10613	73513	23513	20213	20313	23413	11913	10813	11813	20113
40	10119	20119	11319	10619	23519	23519	20219	20419	11019	11919	10819	11819	20119
41	10201	20201	11401	10701	24101	23607	20301	20601	11101	12001	11007	11901	20201
42	10207	20207	11407	10901	24201	24201	20307	24001	0	19901	11101	11907	20207
43	10213	20213	11413	11313	11113	24213	20313	20313	0	0	0	11913	20213
44	10219	20219	11419	11719	11419	24219	20519	20419	19819	24019	24019	24019	0
45	10301	20301	11601	19701	19501	24307	0	20601	19901	24401	24101	11107	20301
46	10307	20307	11607	19707	19507	24401	24301	24201	19907	0	24301	0	0
47	10313	20313	11813	19713	20113	10613	24313	20313	20113	10613	24313	0	0
48	10319	20319	19419	19719	20119	10619	24319	20419	20319	10619	24319	11319	20319
49	10401	20401	20001	19801	20201	10701	24401	20801	20401	10701	24401	11401	20401

time order, i.e., t_n increasing in unit step, from the point t_{no}, say, that was extrapolated into the immediately preceding quarter-day of the season. To help maintain realistic seasonal variations in concentration only the April episode period is used to fill in the Spring (1 April - 20 June) and autumn (20 September - 31 October) months, and only the July and August episode are used to fill in the Summer (20 June - 20 September).

The "0" entries in Table 10 (page 48) indicate that the state $B(I,J,t_n)$ prevailing at the given receptor and time in the season did not occur in the episode, under the constraints described above. There are innumerable ways to "fill in" these gaps of missing values, as we discussed in Section 3. Here we have chosen simply to march across the gap by continuing the episode time sequence that was last in effect. If in this process we reach the end of the episode period before we have completely crossed the gap, we "wrap around" and continue the interpolation from the beginning of the same episode period. In cases where the season begins with missing states, as is the case at receptor (7,2) as indicated in Table 10, the first mapping time is taken from any one of the closest receptors whose factor is not missing. In this way we obtain a complete mapping of the episode into the season.

After the "first pass" extrapolation matrix shown in Table 10 (page 48) has been filled in by the interpolation scheme just described, the result is the matrix shown in Table 11 (page 50). The extrapolation sequence derived for each receptor (see Figure 8, page 52), and each hour in the quarter-day intervals in the episode is mapped one-to-one into the hours in the season. When the final values are applied to the concentration

TABLE 11. SAME AS TABLE 10 AFTER THE MISSING STATES, INDICATED BY ZEROS IN TABLE 10, HAVE BEEN INTERPOLATED USING THE METHOD DESCRIBED IN THE TEXT

MAPPING FACTORS FOR RECEPTOR (I,J):

ICLR=	TIME=(DDDHH) DDD=JULIAN DATE HH=6-HOUR PERIOD (EST) ENDING	(1,2)	(2,2)	(3,2)	(4,2)	(5,2)	(6,2)	(7,2)	(8,2)	(9,2)	(10,2)	(11,2)	(12,2)
1	9201	10601	11207	10607	10401	10401	12001	10901	10601	10601	10601	10601	10601
2	9207	10607	11401	11607	19601	11707	19601	23801	10607	10607	10607	10607	10607
3	9213	10613	11413	20513	20113	19513	20613	23613	10613	10613	10613	10613	10613
4	9219	10619	11419	23319	24119	19519	23819	23419	10619	10619	10619	10619	10619
5	9301	10701	11601	23401	24201	19707	23901	19607	10801	10701	10701	10701	10701
6	9307	10707	11607	23801	24207	20107	24107	19607	10901	11001	10807	10707	10707
7	9313	10713	11813	23813	11113	20213	24313	19813	11313	11013	10813	10813	10813
8	9319	10719	19419	24219	11519	24119	11119	19919	11319	20719	10819	11019	10819
9	9401	10801	19801	23601	11607	10707	11701	20701	11401	20807	11107	11101	10901
10	9407	11001	20807	23607	11607	10707	12001	23407	19601	23401	19507	11101	11007
11	9413	11013	19513	23613	11613	11413	23413	23713	19613	23913	19513	11113	11013
12	9419	11119	23319	23719	19419	11919	23419	23519	11319	19619	19519	11319	19619
13	9501	11201	23401	23801	19501	12001	23507	24301	11401	19801	20607	11401	19701
14	9507	11301	23407	23807	19507	19501	23601	24307	11601	19807	23401	11507	19707
15	9513	11413	23413	23813	20113	19613	24013	24313	11613	19913	23413	11513	19713
16	9519	11419	23419	24219	20119	19619	24119	24319	11619	19919	23419	11519	19719
17	9601	11501	23907	24301	23401	19701	24401	24401	11707	20007	23501	11601	19801
18	9607	11601	24001	10707	23701	19801	10707	10601	11707	10707	23507	19907	19807
19	9613	11613	24013	10713	23813	11713	10713	10613	11813	11013	19813	19913	24013
20	9619	11619	24019	11119	23819	11719	10719	10719	11819	11019	19819	19619	24119
21	9701	11701	24101	11407	23901	12001	10801	11101	11901	19707	19507	19701	24201
22	9707	12001	24107	12007	11607	19501	20601	11107	10907	24001	11001	19707	24207
23	9713	19613	24113	20013	11613	19613	20713	11113	10913	24013	11013	19713	24213
24	9719	19719	24119	20219	11619	11619	20719	24119	10909	10719	11019	19719	19619
25	9801	19801	24301	20301	19501	20107	24301	20501	11001	10907	11101	10901	19701
26	9807	19807	24307	20307	19507	20201	24401	20601	20107	10907	24007	11301	19707
27	9813	19813	24313	20313	20113	20213	10613	24313	20113	11013	24013	11613	19713
28	9819	19819	24319	20419	20119	20219	10619	24319	20319	11019	24219	11419	19719
29	9901	19901	24401	23801	20201	20301	10701	24401	20401	11101	24301	11507	19801
30	9907	19907	10607	23807	20207	20307	10801	10601	20407	11201	24307	11601	19807
31	9913	19913	10613	23813	20213	20313	10913	10613	20413	11513	24313	11613	19813
32	9919	19919	10619	24219	20219	20319	11019	10619	20419	11619	24319	11619	19819
33	10001	20001	10701	24301	20301	20407	11107	10701	20501	11701	24401	11701	19901
34	10007	20007	10707	24307	20307	20501	11301	10707	20507	11707	19601	11707	19907
35	10013	20013	10713	24313	20314	20713	19713	11113	20513	11713	19613	11713	19913
36	10019	20019	10919	24319	20419	23419	19819	11819	20519	11819	19619	11719	19919
37	10101	20101	11107	24401	20501	23501	19907	11901	20807	11901	10701	11801	20001
38	10107	20107	11201	10607	20807	23507	20107	11907	23407	11907	10807	11807	20007
39	10113	20113	11313	10613	23513	23513	20213	20313	23413	11913	10813	11813	20113
40	10119	20119	11319	10619	23519	23519	20219	20419	11019	11919	10819	11619	20119
41	10201	20201	11401	10701	24101	23607	20301	20601	11101	12001	11007	11901	20201
42	10207	20207	11407	10901	24201	24201	20307	24001	11107	19901	11101	11907	20207
43	10213	20213	11413	11313	11113	24213	20313	20313	11113	19913	11113	11913	20213
44	10219	20219	11419	11719	11419	24219	20519	20419	19819	24019	24019	24019	20219
45	10301	20301	11601	19701	19501	24307	20601	20601	19901	24401	24101	11107	20301
46	10307	20307	11607	19707	19507	24401	24301	24201	19907	23407	24301	11107	20307
47	10313	20313	11813	19713	20113	10613	24313	20313	20113	10613	24313	11113	20313
48	10319	20319	19419	19719	20119	10619	24319	20419	20319	10619	24319	11319	20319
49	10401	20401	20001	19801	20201	10701	24401	20801	20401	10701	24401	11401	20401

differences predicted by the model for given emissions changes, the outcome is hourly values of delta concentrations at each hour of the season in each ROM grid cell. These values may then be processed in any desired manner to arrive at estimates of the seasonal impact of given emissions changes.

In the next Section, we describe the base and controlled emissions examined in this study, and we describe the meteorological and observed air quality characteristics of the 3 episode periods for which the model simulations are performed.

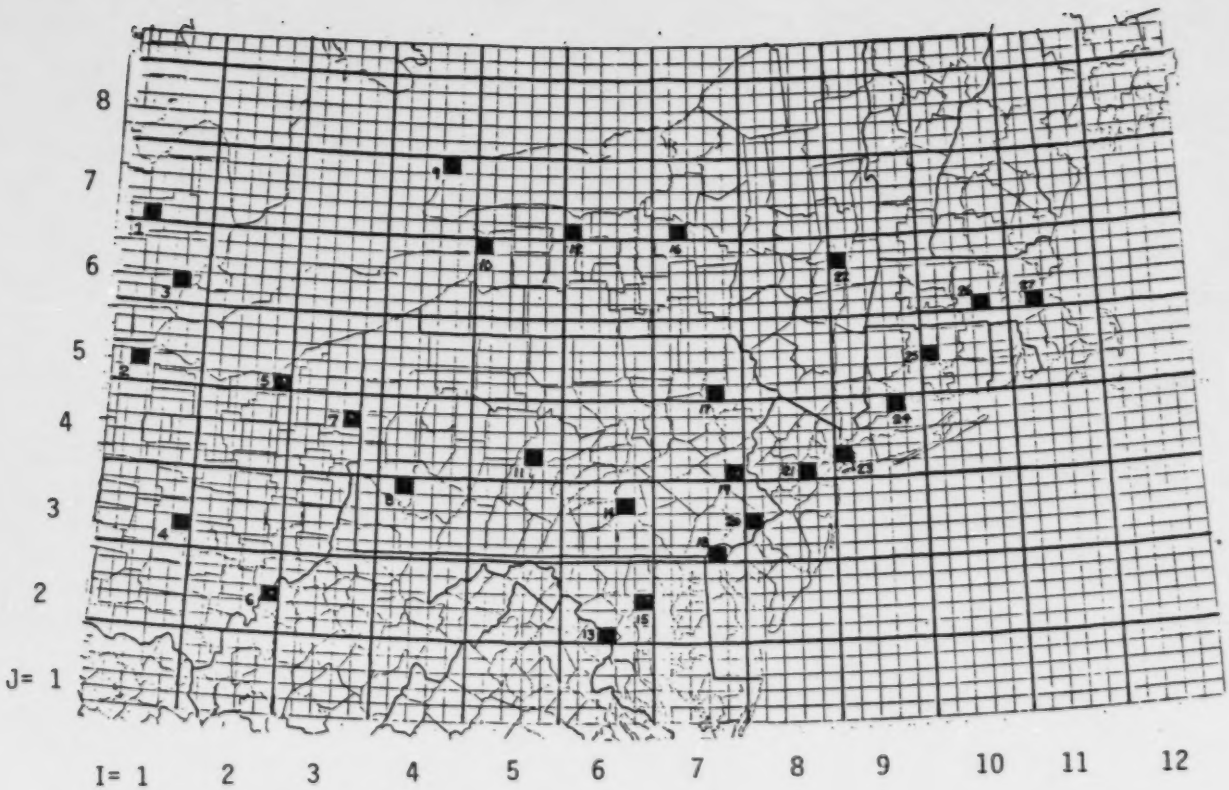

Figure 8. Locations of the 27 sources considered in the preliminary implementation of the seasonal extrapolation scheme. Large grid cells labeled (I,J) I=1,12, J=1,9 are the receptor sites. Small cells are the ROM grid.

SECTION 5

METEOROLOGY OF THE EPISODES AND SPECIFICATIONS OF THE EMISSIONS CONTROL STRATEGIES

METEOROLOGICAL CONDITIONS DURING THE THREE EPISODE PERIODS

We have argued in earlier reports that in the context of modeling air quality over 1000 km scale domains and periods of many days, the best description of the meteorological conditions prevailing during the simulation is implicit in the ozone concentrations observed in the study area during the period modeled. There were some 200 SAROAD sites measuring ozone in 1980 in the portion of the Northeastern U.S. simulated in the present study. The median of the daily maximum O_3 values measured at these sites each day in 1980 is plotted in Figure 9 (page 56). The maximum value observed within the domain each day is also plotted. Looking at the level and behavior of the median and maximum ozone values within each of the three episode periods delineated in Figure 9, and comparing these with the corresponding values observed during the remainder of the year, one gets an overall view of the weather conditions implicit in the model simulations. It is readily apparent from Figure 9 that the meteorology prevalent during the episode is not representative of the year as a whole but rather it is heavily biased toward conditions favorable to high ozone levels. This bias was deliberately created because it is the extreme ozone concentrations that are of concern in regulatory studies. However, as we shall see later there is evidence in the model results that the effects of emissions controls on ozone are sensitive to meteorological

conditions. Consequently, it is possible that the episode periods we have selected are not a good basis for estimating the ozone reductions that would occur over the season as a result of specific emissions controls. One could argue that errors resulting from a lack of representativeness of the chosen meteorology are probably not significantly larger than those inherent in the extrapolation procedure itself.

Another point to keep in mind is that the vast majority of the SAROAD monitoring stations are situated within or near urban areas. For this reason the data plotted in Figure 9 are not necessarily representative conditions that existed in rural and remote areas. Experiments performed with the first-generation ROM suggested that in remote areas ozone levels may sometimes peak one or two days after the highest concentrations occurred in urban areas.

SPECIFICATIONS OF THE EMISSIONS CONTROLS

Each of the three episode periods was simulated using each of three emissions inventories: a base case and two control strategies. Each of these inventories consists of two parts: the emissions of anthropogenic sources and the emissions (hydrocarbon only) from natural sources. The latter component was described earlier in Section 2, and it is the same in all three inventories. In other words, neither of the two emissions control strategies that we consider assumes any change in natural emissions.

The anthropogenic component of the base case inventory is the NAPAP 5.3 data (see Toothman, et al., 1984). Each of the two control strategies was created from the base inventory by modifying the hydrocarbon emissions

in the following way:

Control strategy #1 = projected 1987 baseline emissions taking into account growth since 1980 plus VOC reductions from New Source Performance Standards (NSPS), plus VOC reductions from the Federal Motor Vehicle Control Program (RMVCP). See Appendix A for county-by-county emissions reductions;

Control strategy #2 = control strategy #1 plus an additional across-the-board 22% reduction (from the base case) in VOC to reflect FMVCP reductions projected to 1995.

In general, control strategy #1 assumes an 8% reduction in VOC emissions from attainment counties and reductions ranging from about 5% to 50% in nonattainment counties (see Appendix A). There are no NO_x emissions reductions in this strategy. Control strategy #2 is simply strategy #1 with an additional 22% reduction in VOC assumed everywhere. There are no NO_x emissions reductions in this strategy; and as we noted earlier neither strategy assumes any change in biogenic emissions from the base levels.

Figure 10 (page 57) shows where the emissions reductions proposed in strategy #1 change source strengths most. Only grid cells in which VOC emissions are reduced more than 1000 kg/hr are highlighted.

In the next section we examine the model results.

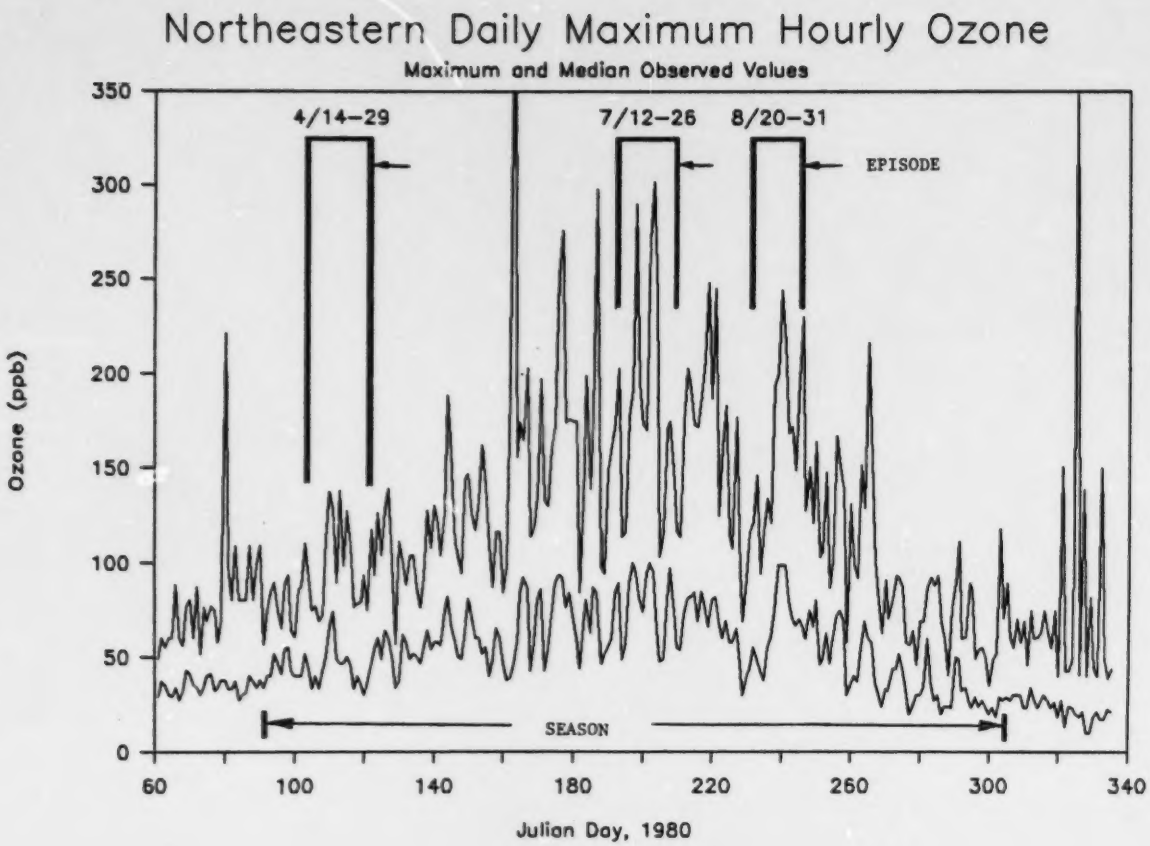

Figure 9. Maximum and median daily maximum ozone concentration measured at some 200 SAROAD stations in the Northeastern U.S. in 1980. The three episode periods modeled by the ROM are noted at the top; the season is noted at the bottom.

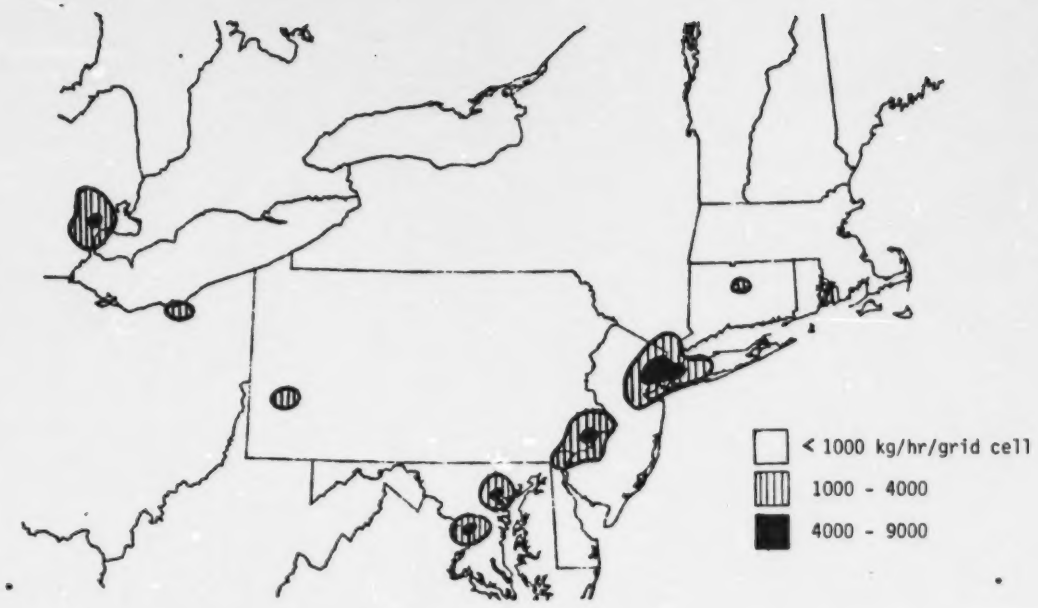

Figure 10. Reductions in VOC emissions (kg/hr/grid cell) from the 1980 base levels assumed in control strategy #1. Only grid cells with reductions larger than 1000 kg/hr are shown. The NO_x and natural hydrocarbon emissions are unchanged.

SECTION 6

MODEL RESULTS

In this section we examine the results of the ROM simulations of the base case emissions and the two emissions control strategies. We will look at the simulated effects of controls in each of the episode periods separately and the effects extrapolated to the entire season.

Let us look first at the spatial pattern of the effects of control strategy #1 on peak O_3 concentration in each of the three episode periods. Figures 11-13 (pages 62-64) show the maximum O_3 concentration predicted in each period using the base case emissions (top panel of each figure) and the reduction in peak concentration brought about by the emissions controls (lower panel of each figure). The simulated effects of control strategy #2 are very similar to those shown in Figures 11-13 and will not be presented here.

The model results indicate that for the most part the emissions controls reduce peak concentrations most in the areas where the concentration are highest. In this respect this control strategy represents an efficient step toward attainment of the ozone standard. This attribute is apparently due to the fact that in both control plans, the largest emissions reductions are imposed on the sources that impact air quality in areas where the highest O_3 concentrations occur. Another important attribute of these strategies is that, in general, they lower ozone levels everywhere and in all three episodes.

Next we examine the effects of the emissions controls on the frequency of occurrence of given hourly O_3 concentrations during each of the episode periods. To facilitate the discussions, we have collected all receptors into two groups: MSA's (Metropolitan Statistical Areas) and non-MSAs. Appendix B lists the counties that fall into each group and Figures 14 and 15 (pages 65 and 66) show their locations. In Figure 14 the MSA counties are divided into two subgroups based on the density of VOC and NO_x emissions in each county; and in Figure 15 the non-MSA counties are split into two subgroups based on land use.

Figure 16 (page 67) compares the cumulative frequency distribution of predicted hourly O_3 concentrations in the MSA counties in the base case with those obtained using control strategy #1. Results from each of the episode periods are shown separately. The corresponding values for the non-MSA counties are given in Figure 17 (page 68). The results are presented in the form of quantile-quantile (QQ) plots described earlier. Keep in mind that in these graphs the predicted O_3 concentrations in the base and control cases are not paired in either time or space.

The following example will aid the interpretation of the results. Looking at the center panel of Figure 16, we see that in the July episode the 99.5 percentile level of the O_3 concentrations in the control case is about 125 ppb (read from the ordinate of the graph). This means that 5 observations in 1000 equal or exceed 125 ppb in the MSA counties during the July episode meteorological conditions with the VOC emission controls proposed in strategy #1 in effect. Referring to the same graph and following the dashed line up from the 125 ppb point on the abscissa,

which represents the base case concentrations, we find that 125 ppb is between the 97-th and 98-th percentile value of the base case concentrations, indicating that in the base case O_3 exceeds the 125 ppb level between 20 and 30 times in every 1000 observations. Thus, the 125 ppb threshold is exceeded about 5 times as often in the base case as in the control case.

The results presented in Figures 16 and 17 reveal the following:

(1) O_3 concentrations are either reduced by the VOC emissions reductions specified in control strategy #1 or they are unchanged. (If the controls caused an increase in concentration anywhere at any time, the locus of the points in the QQ plots would lie above the unit-slope straight line where the base case concentrations were exceeded);

(2) The emissions controls have no significant effect on concentrations below roughly the 90-th percentile value. This point is between 80 and 90 ppb O_3 in the two summer scenarios and about 70 ppb in the spring episode;

(3) The controls are less effective in reducing the maximum O_3 concentration in the August episode than in the other two periods. This effect is most pronounced in the non-MSA counties. It indicates that the effectiveness of emissions controls is a function of meteorological conditions. One can expect that the degree of sensitivity of control effects to meteorology varies from location to location depending on the local spatial distribution of sources;

(4) Considering the fact that the ozone design value is roughly the 99.98 percentile concentration, a point very near the maximum value (or 100-th percentile) represented by the "o" on each of the QQ plots; and considering the tendency of the ROM to underpredict

extreme O_3 values, as we noted earlier, we conclude that in order for a control strategy to reduce peak ozone to 120 ppb, it would have to yield QQ plots like those given in Figures 16 and 17 in which the maximum point lies near the 100 ppb level of the y-axis. Clearly, control strategy #1 falls far short of meeting this requirement.

Upon extrapolating the base and control case ozone concentrations from the three episodes periods to the season, we obtain the frequency relationships shown by the QQ plots in Figure 18 (page 69). These results show nearly the same impact of the controls on concentrations in both the MSA and non-MSA counties. In both bases there is virtually no effect on concentrations below about the 95-th percentile level.

Figure 19 (page 70) shows the additional benefits gained by the added emissions reductions of control strategy #2. (Recall that strategy #2 consists of an additional 22% reduction in VOC emissions across the board.) Figure 19 compares the seasonal frequency distribution of predicted hourly O_3 concentrations in control strategies #1 (abscissa) and control strategy #2 (ordinate). We see that the additional emissions reductions have lowered the peak O_3 values only slightly from that achieved by control strategy #1, and that the added controls have little effect on concentrations below about the 98-th percentile level. According to the model results, the additional controls imposed by strategy #2 are insufficient to attain the O_3 standard in either the MSA or non-MSA counties. A model like the ROM could be used to find optimal control measures to achieve the standard, but such an exercise would require large amounts of computer time and an accurate inventory of existing sources.

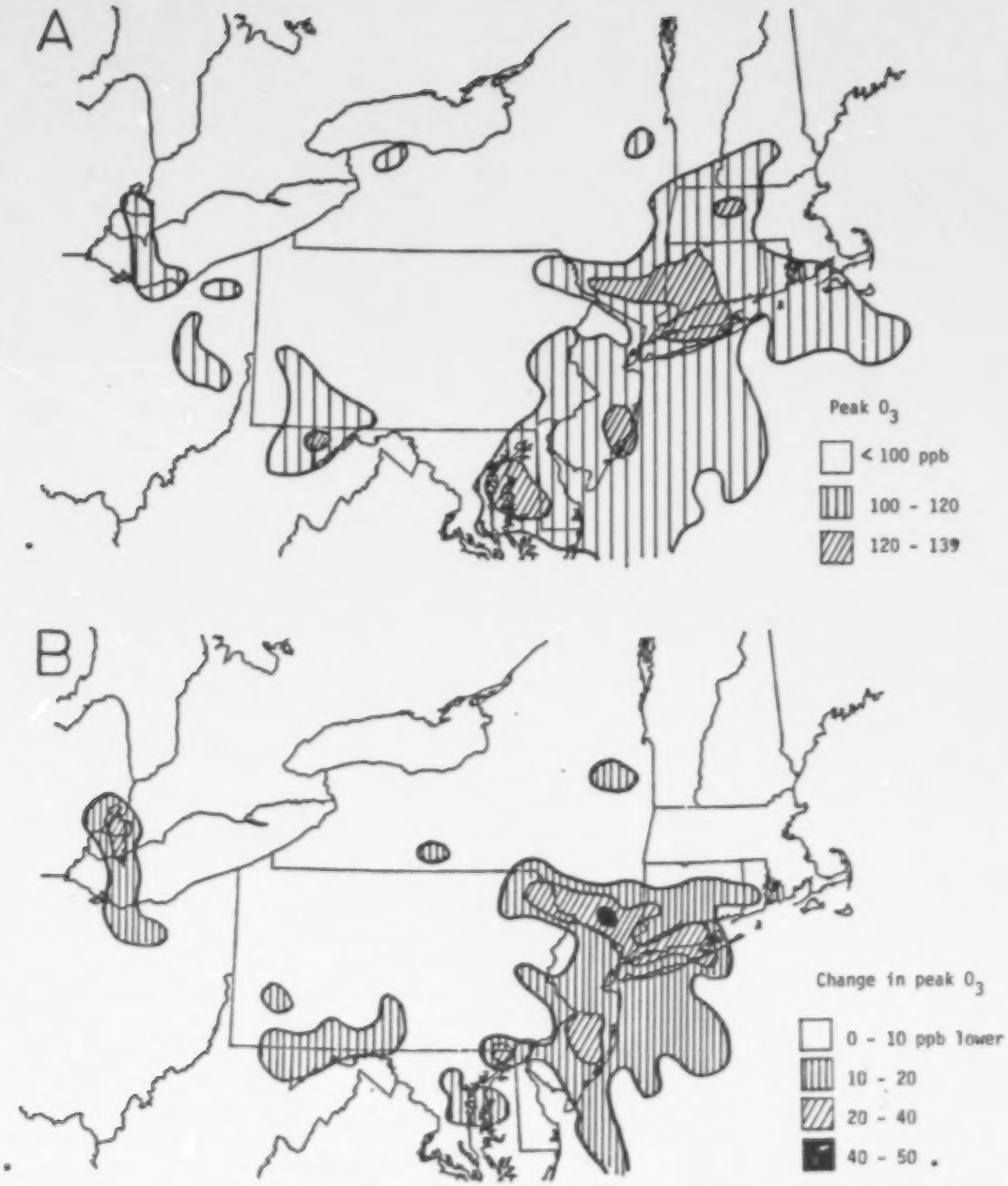

Figure 11 (a). Maximum O_3 predicted for the April episode using base case emissions;

(b). Change in episode peak effected by control strategy #1. Values plotted are (base case peak O_3 minus control case peak O_3).

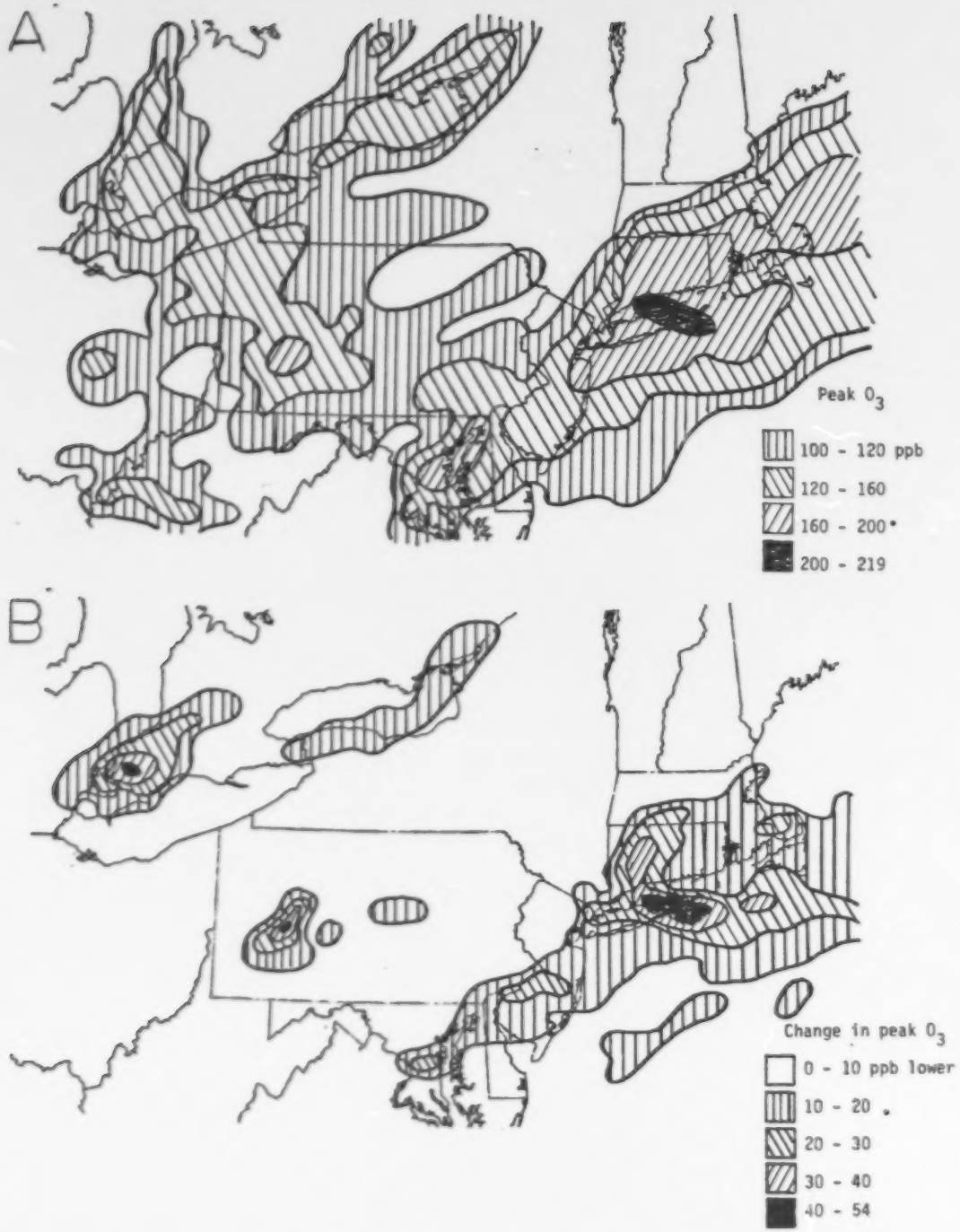

Figure 12. Same as Figure 11 except results are from the simulations of the July episode.

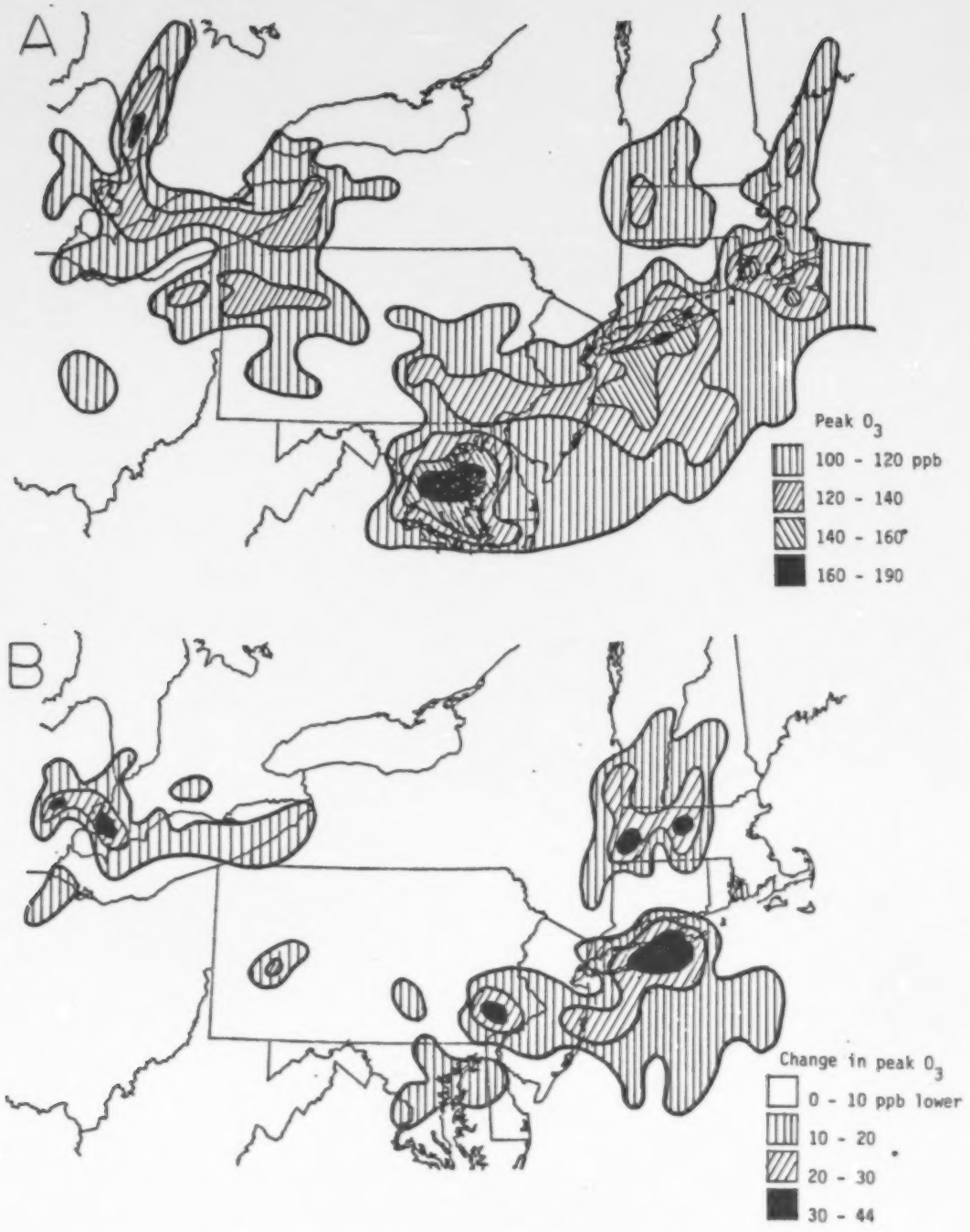

Figure 13. Same as Figure 11 except results are from the simulations of the August 1980 episode.

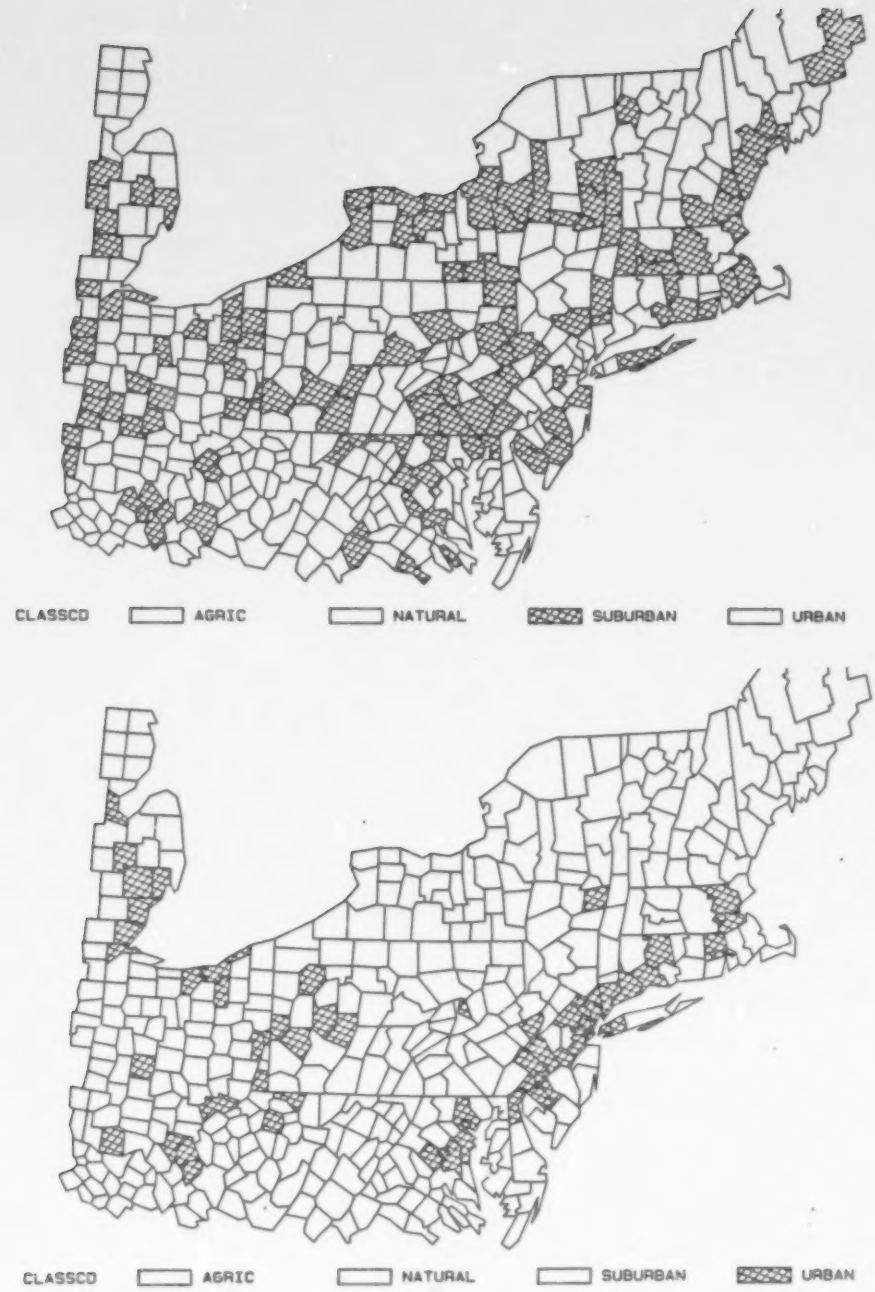

Figure 14. Metropolitan Statistical Areas (MSAs) divided into two groups based on emissions. Counties shown in the lower panel are the top 50 NO_x and VOC emitters in the Northeast, based on emissions density (mass/area/time). Top panel shows all other MSA counties.

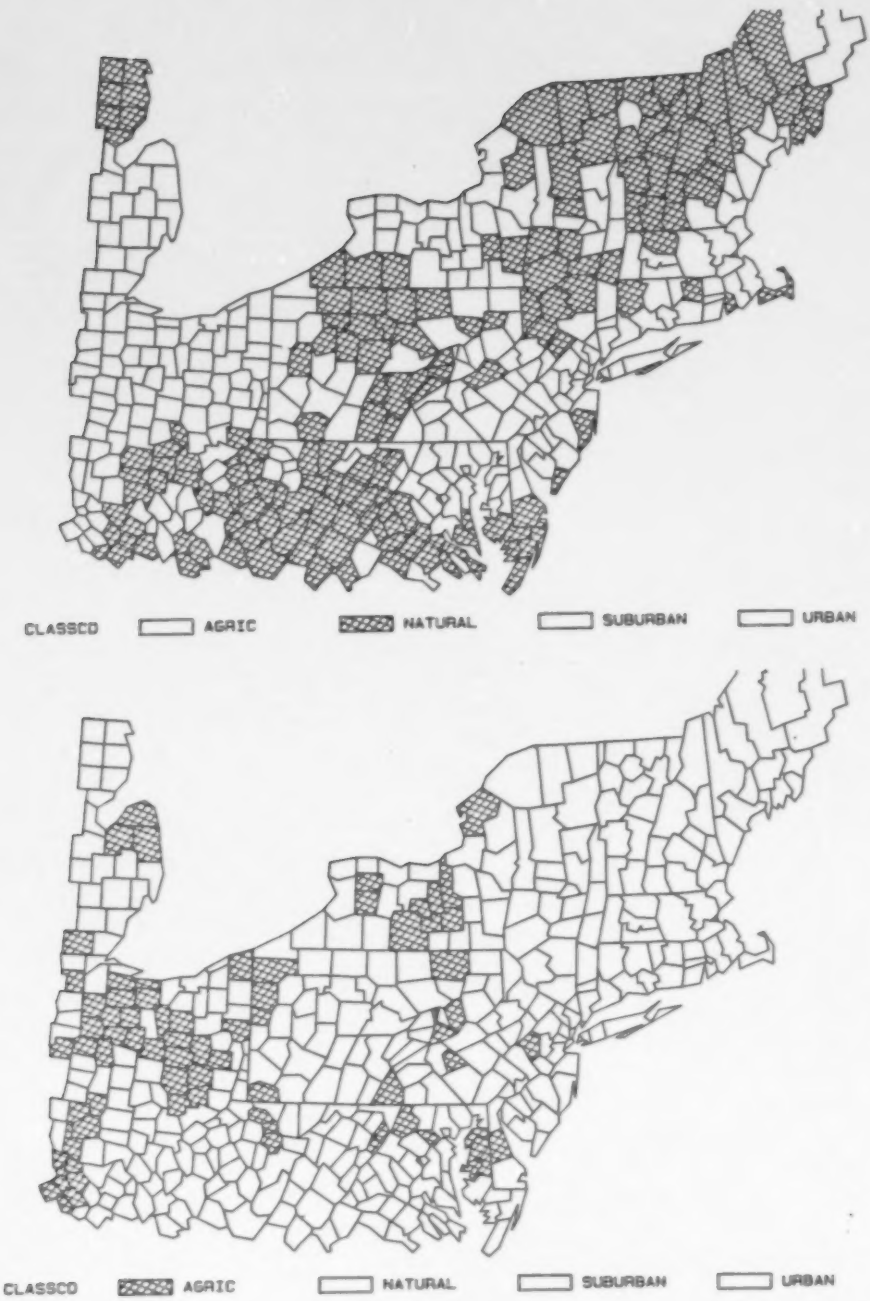

Figure 15. Non-MSA counties divided according to land use. Counties in the lower panel are predominantly agricultural. Those in the top panel are predominately natural.

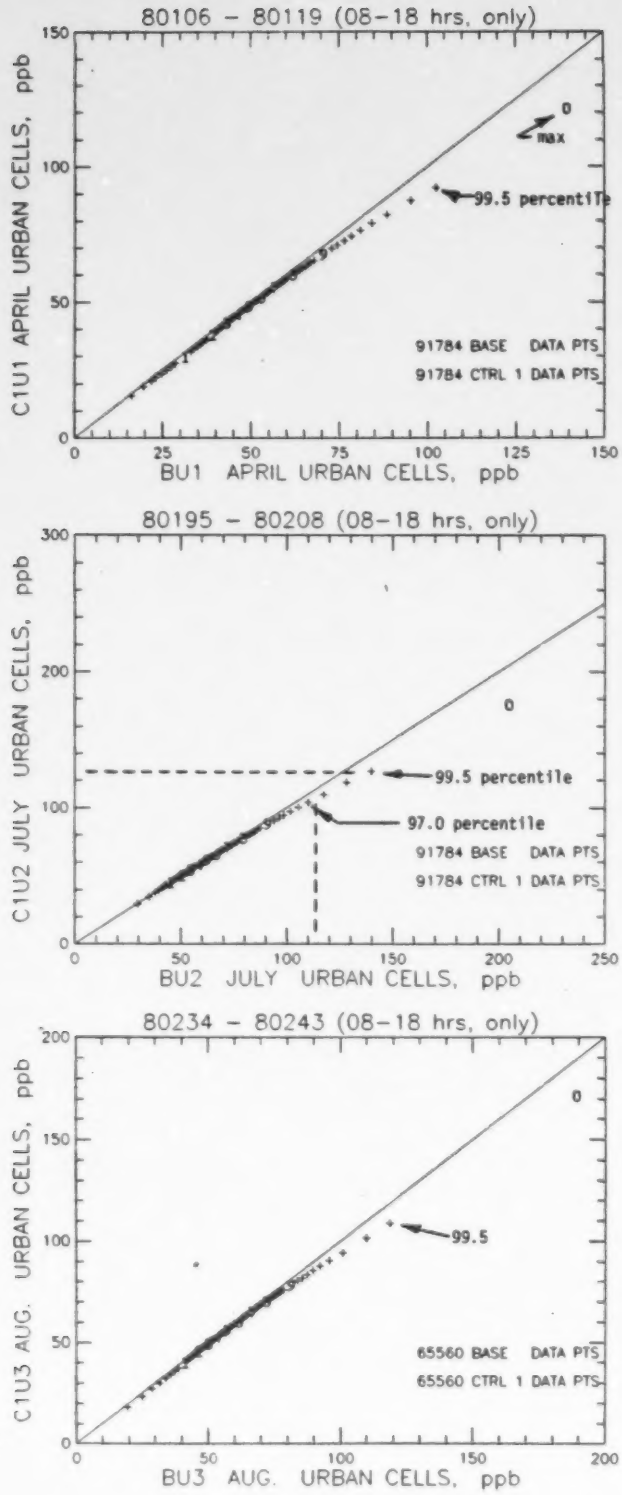

Figure 16. Effects of emission control strategy #1 on the cumulative frequency of hourly ozone values in MSA counties (referred to as "urban cells" in the graphs) in each of the three episode periods. See text for discussion.

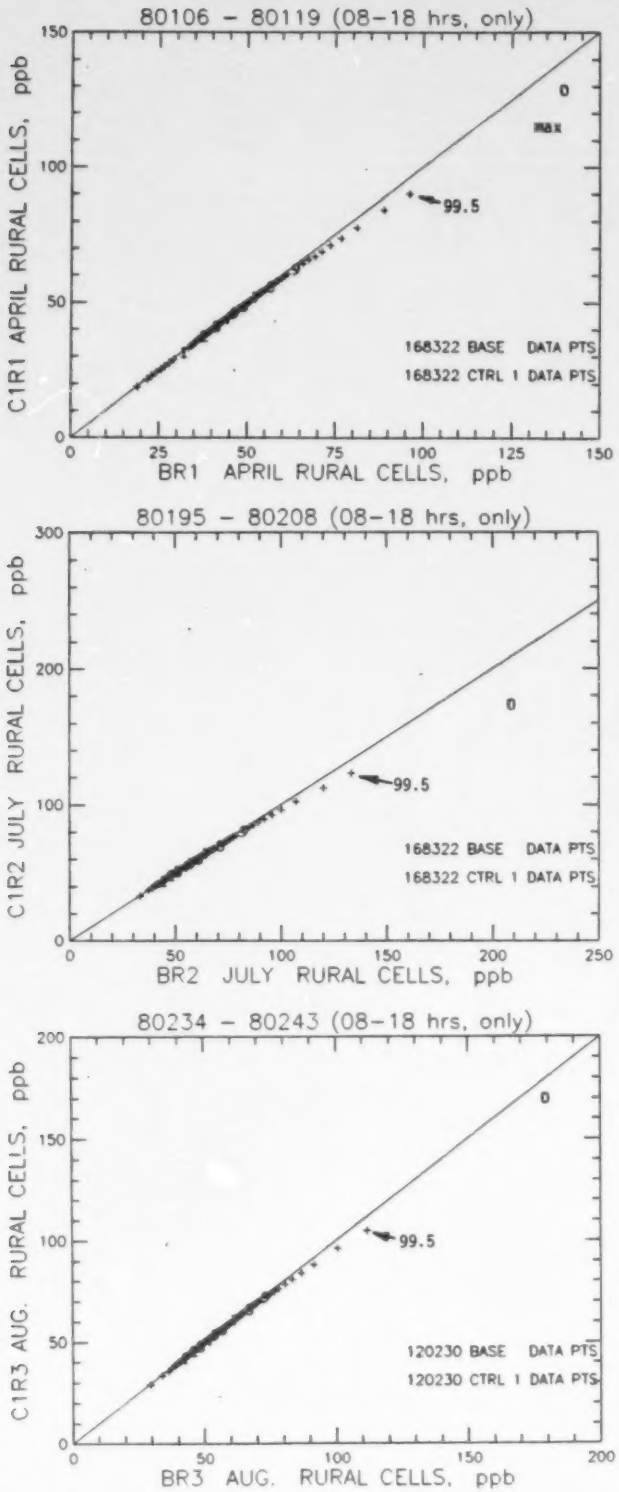

Figure 17. Same as Figure 16 except results are for non-MSA counties referred to as "rural cells" in the graphs).

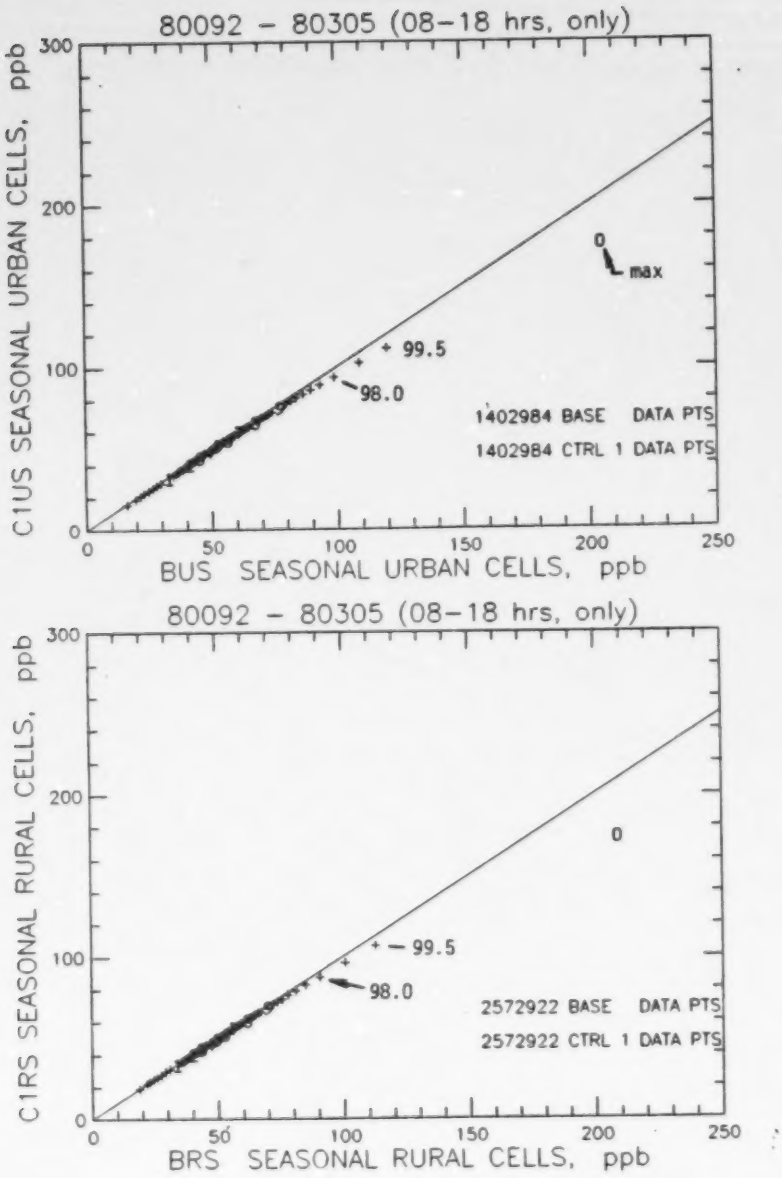

Figure 18. Comparison of the frequency distributions of hourly ozone concentrations extrapolated from the episode to the season (April-October 1980) for the base case (abscissa) and control strategy #1 (ordinate) in MSA (urban cells) and non-MSA (rural cells) sites.

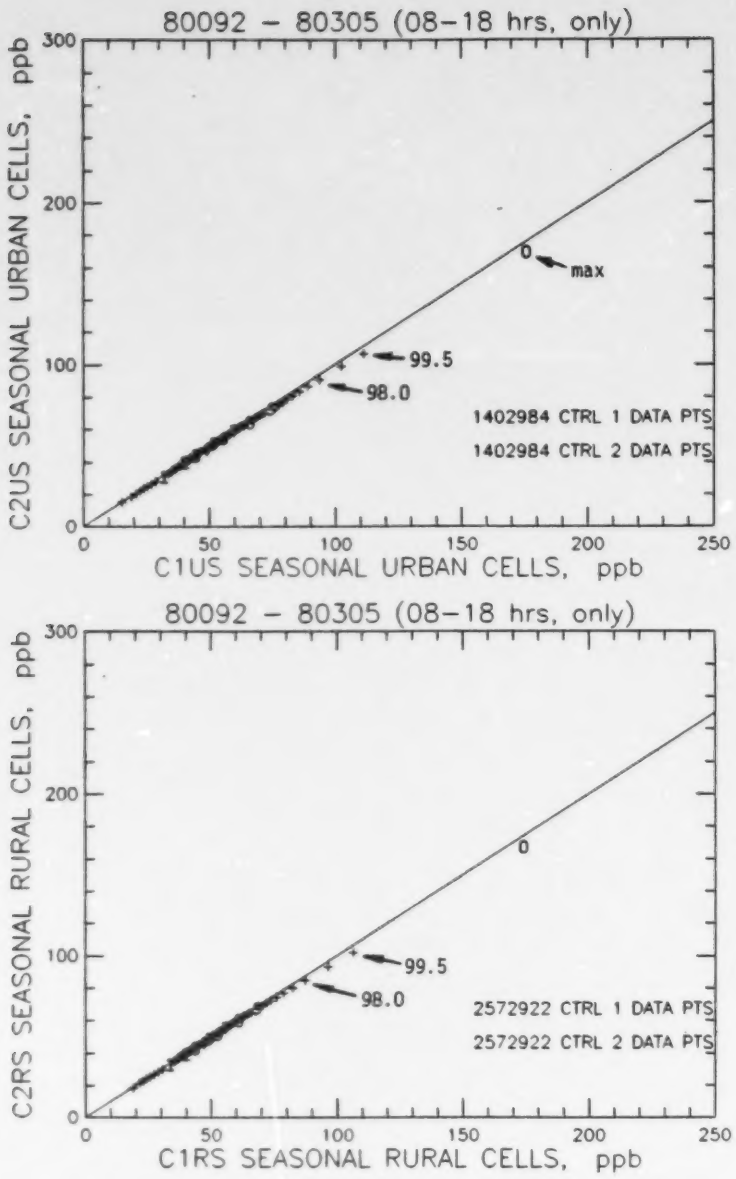

Figure 19. Comparison of the cumulative frequency distributions of ozone predicted using control strategy #2 (ordinate) with that of strategy #1 (abscissa) in MSA (urban cells) and non-MSA (rural cells) locations. Values shown are seasonal extrapolations.

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APPENDIX A

EMISSIONS CHANGES BY COUNTY

The county-by-county control strategy emissions inventory expressed as percentage change in hydrocarbon and NO_x emissions from the 1980 base emissions rates. Emissions changes represent 1987 projections based on 1982 SIPs.

Notes:

(1) Unspecified changes in hydrocarbon (HC) or nitrogen oxides (NO) indicate that the default values apply, namely -8% for HC and 0% for NO_x in control strategy #1. In control strategy #2 all hydrocarbon reduction percentages are increased by 22, including the default value which becomes -30%. There is no reduction of NO_x in control strategy #2.

(2) Six digit numbers before county names are the NEDS county ID's. The first two of the six digits identify the state as follows:

07	Connecticut
08	Delaware
09	District of Columbia
18	Kentucky
20	Maine
21	Maryland
22	Massachusetts
23	Michigan
30	New Hampshire
31	New Jersey
33	New York
36	Ohio
39	Pennsylvania
41	Rhode Island
47	Vermont
48	Virginia
50	West Virginia

1.	070265	FAIRFIELD CO	HC -28.4	NO
2.	070425	HARTFORD CO	HC -30.8	NO
3.	070473	LITCHFIELD CO	HC -27.7	NO
4.	070565	MIDDLESEX CO	HC -28.1	NO
5.	070705	NEW HAVEN CO	HC -30.3	NO
6.	070725	NEW LONDON CO	HC -28.7	NO
7.	071155	TOLLAND CO	HC -30.1	NO
8.	071505	WINDHAM CO	HC -23.0	NO
9.	080060	KENT CO	HC	NO
10.	080180	NEW CASTLE CO	HC -40.2	NO
11.	080240	SUSSEX CO	HC	NO
12.	090020	WASHINGTON	HC -39.7	NO
13.	180180	BATH CO	HC	NO
14.	180300	BOURBON CO	HC	NO
15.	180340	BOYD CO	HC	NO
16.	180380	BRACKEN CO	HC	NO
17.	180620	CARTER CO	HC	NO
18.	180720	CLARK CO	HC -38.1	NO
19.	181060	ELLIOTT CO	HC	NO
20.	181200	FLEMING CO	HC	NO
21.	181540	GREENUP CO	HC	NO
22.	182140	LAWRENCE CO	HC	NO
23.	182280	LEWIS CO	HC	NO
24.	182640	MASON CO	HC	NO
25.	182720	MENIFEE CO	HC	NO
26.	182860	MONTGOMERY CO	HC	NO
27.	182900	MORGAN CO	HC	NO
28.	183040	NICHOLAS CO	HC	NO
29.	183520	ROBERTSON CO	HC	NO
30.	183560	ROWAN CO	HC	NO
31.	200027	ANDROSCOGGIN CO	HC	NO
32.	200277	CUMBERLAND CO	HC	NO
33.	200445	FRANKLIN CO	HC	NO
34.	200547	KENNEBEC CO	HC	NO
35.	200595	KNOX CO	HC	NO
36.	200645	LINCOLN CO	HC	NO
37.	200885	OXFORD CO	HC	NO
38.	200907	PENOBSCOT CO	HC	NO
39.	201065	SAGADAHOC CO	HC	NO
40.	201125	SOMERSET CO	HC	NO
41.	201183	WALDO CO	HC	NO
42.	201325	YORK CO	HC	NO
43.	210040	ALLEGANY CO	HC	NO
44.	210080	ANNE ARUNDEL CO	HC -44.2	NO
45.	210120	BALTIMORE	HC -44.2	NO
46.	210140	BALTIMORE CO	HC -44.2	NO
47.	210280	CALVERT CO	HC	NO
48.	210340	CAROLINE CO	HC	NO
49.	210360	CARROLL CO	HC -44.2	NO
50.	210420	CECIL CO	HC	NO
51.	210440	CHARLES CO	HC	NO
52.	210600	DORCHESTER CO	HC	NO
53.	210740	FREDERICK CO	HC	NO
54.	210800	GARRETT CO	HC	NO
55.	210920	HARFORD CO	HC -44.2	NO

56.	210960	HOWARD CO	HC -44.2	NO
57.	211000	KENT CO	HC	NO
58.	211160	MONTGOMERY CO	HC -34.9	NO
59.	211300	PRINCE GEORGES CO	HC -36.6	NO
60.	211320	QUEEN ANNES CO	HC	NO
61.	211400	ST MARYS CO	HC	NO
62.	211500	SOMERSET CO	HC	NO
63.	211600	TALBOT CO	HC	NO
64.	211680	WASHINGTON CO	HC	NO
65.	211740	WICOMICO CO	HC	NO
66.	211800	WORCESTER CO	HC	NO
67.	228001	BARNSTABLE	HC -12.4	NO
68.	228002	BERKSHIRE	HC -9.8	NO
69.	228003	BRISTOL	HC -12.4	NO
70.	228004	DUKES	HC -12.4	NO
71.	228005	ESSEX	HC -7.8	NO
72.	221291	ESSEX	HC -7.8	NO
73.	228006	FRANKLIN	HC -8.7	NO
74.	228007	HAMPDEN	HC -8.7	NO
75.	221798	HAMPDEN	HC -8.7	NO
76.	228008	HAMPSHIRE	HC -8.7	NO
77.	228009	MIDDLESEX	HC -7.8	NO
78.	221274	MIDDLESEX	HC -7.8	NO
79.	228010	NANTUCKET	HC -12.4	NO
80.	228011	NORFOLK	HC -7.8	NO
81.	228012	PLYMOUTH	HC -12.4	NO
82.	222121	PLYMOUTH	HC -12.4	NO
83.	228013	SUFFOLK	HC -7.8	NO
84.	228014	WORCHESTER	HC -20.0	NO
85.	220369	WORCHESTER	HC -20.0	NO
86.	230060	ALCONA CO	HC	NO
87.	230220	ALPENA CO	HC	NO
88.	230280	ARENAC CO	HC	NO
89.	230400	BAY CO	HC	NO
90.	231700	GENESEE CO	HC	NO
91.	232340	HURON CO	HC	NO
92.	232440	IOSCO CO	HC	NO
93.	232880	LAPEER CO	HC	NO
94.	232960	LENAWEE CO	HC	NO
95.	233020	LIVINGSTON CO	HC	NO
96.	233140	MACOMB CO	HC -34.7	NO
97.	233600	MONROE CO	HC	NO
98.	233640	MONTMORENCY CO	HC	NO
99.	233930	OAKLAND CO	HC -45.2	NO
100.	234040	OGEMAW CO	HC	NO
101.	234100	OSCODA CO	HC	NO
102.	234620	ST CLAIR CO	HC -41.8	NO
103.	234780	SAGINAW CO	HC	NO
104.	234880	SANILAC CO	HC	NO
105.	234860	SHIAWASSEE CO	HC	NO
106.	235160	TUSCOLA CO	HC	NO
107.	235200	WASHTENAW CO	HC	NO
108.	235320	WAYNE CO	HC -38.3	NO
109.	300020	BELKNAP CO	HC	NO
110.	300060	CARROLL CO	HC	NO
111.	300080	CHESHIRE CO	HC	NO
112.	300140	COOS CO	HC	NO

113.	300240	GRAFTON CO	HC	NO
114.	300300	HILLSBOROUGH CO	HC	NO
115.	300440	MERRIMACK CO	HC	NO
116.	300580	ROCKINGHAM CO	HC	NO
117.	300640	STRAFFORD CO	HC	NO
118.	300660	SULLIVAN CO	HC	NO
119.	310080	ATLANTIC CO	HC -29.5	NO
120.	310300	BERGEN CO	HC -35.9	NO
121.	310660	BURLINGTON CO	HC -34.9	NO
122.	310740	CAMDEN CO	HC -34.5	NO
123.	310780	CAPE MAY CO	HC -24.8	NO
124.	311050	CUMBERLAND CO	HC -31.6	NO
125.	311330	ESSEX CO	HC -34.7	NO
126.	311760	GLOUCESTER CO	HC -46.8	NO
127.	312240	HUDSON CO	HC -28.0	NO
128.	312260	HUNTERDON CO	HC -35.3	NO
129.	312930	MERCER CO	HC -32.2	NO
130.	313060	MIDDLESEX CO	HC -39.6	NO
131.	313180	MONMOUTH CO	HC -37.2	NO
132.	313260	MORRIS CO	HC -39.7	NO
133.	313900	OCEAN CO	HC -27.5	NO
134.	314120	PASSAIC CO	HC -33.5	NO
135.	314900	SALEM CO	HC -49.2	NO
136.	315020	SOMERSET CO	HC -33.8	NO
137.	315300	SUSSEX CO	HC -33.4	NO
138.	315440	UNION CO	HC -39.1	NO
139.	315660	WARREN CO	HC -41.0	NO
140.	330060	ALBANY CO	HC	NO
141.	330120	ALLEGANY CO	HC	NO
142.	330600	BRONX CO	HC -28.9	NO
143.	330640	BROOME CO	HC	NO
144.	330840	CATTARAUGUS CO	HC	NO
145.	330860	CAYUGA CO	HC	NO
146.	331000	CHAUTAUQUA CO	HC	NO
147.	331060	CHEMUNG CO	HC	NO
148.	331080	CHENANGO CO	HC	NO
149.	331120	CLINTON CO	HC	NO
150.	331220	COLUMBIA CO	HC	NO
151.	331400	CORTLAND CO	HC	NO
152.	331520	DELAWARE CO	HC	NO
153.	331620	DUTCHESS CO	HC	NO
154.	332000	ERIE CO	HC	NO
155.	332020	ESSEX CO	HC	NO
156.	332240	FRANKLIN CO	HC	NO
157.	332340	FULTON CO	HC	NO
158.	332400	GENESEE CO	HC	NO
159.	332660	GREENE CO	HC	NO
160.	332820	HAMILTON CO	HC	NO
161.	332960	HERKIMER CO	HC	NO
162.	333340	JEFFERSON CO	HC -26.7	NO
163.	333440	KINGS CO	HC	NO
164.	333740	LEWIS CO	HC	NO
165.	333880	LIVINGSTON CO	HC	NO
166.	334040	MADISON CO	HC	NO
167.	334380	MONROE CO	HC	NO
168.	334400	MONTGOMERY CO	HC -44.2	NO
169.	334520	NASSAU CO		

170.	334660	NEW YORK CO	HC -29.4	NO
171.	334720	NIAGARA CO	HC	NO
172.	335060	ONEIDA CO	HC	NO
173.	335100	ONONDAGA CO	HC	NO
174.	335120	ONTARIO CO	HC	NO
175.	335140	ORANGE CO	HC	NO
176.	335180	ORLEANS CO	HC	NO
177.	335240	OSWEGO CO	HC	NO
178.	335260	OTSEGO CO	HC	NO
179.	335640	PUTNAM CO	HC	NO
180.	335660	QUEENS CO	HC -36.0	NO
181.	335700	RENSSELAER CO	HC	NO
182.	335720	RICHMOND CO	HC -27.6	NO
183.	335780	ROCKLAND CO	HC -37.6	NO
184.	335930	ST. LAWRENCE CO	HC	NO
185.	335965	SARATOGA CO	HC	NO
186.	336040	SCHENECTADY CO	HC	NO
187.	336060	SCHOHARIE CO	HC	NO
188.	336080	SCHUYLER CO	HC	NO
189.	336160	SENECA CO	HC	NO
190.	336500	STEUBEN CO	HC	NO
191.	336580	SUFFOLK CO	HC -37.3	NO
192.	336600	SULLIVAN CO	HC	NO
193.	336700	TIOGA CO	HC	NO
194.	336720	TOMPKINS CO	HC	NO
195.	336840	ULSTER CO	HC	NO
196.	337040	WARREN CO	HC	NO
197.	337100	WASHINGTON CO	HC	NO
198.	337240	WAYNE CO	HC	NO
199.	337320	WESTCHESTER CO	HC -46.7	NO
200.	337580	WYOMING CO	HC	NO
201.	337600	YATES CO	HC	NO
202.	360040	ADAMS CO	HC	NO
203.	360080	ALLEN CO	HC	NO
204.	360180	ASHLAND CO	HC	NO
205.	360220	ASHTABULA CO	HC	NO
206.	360260	ATHENS CO	HC	NO
207.	360280	AUGLAIZE CO	HC	NO
208.	360540	BELMONT CO	HC	NO
209.	360820	BROWN CO	HC	NO
210.	361040	CARROLL CO	HC	NO
211.	361140	CHAMPAIGN CO	HC	NO
212.	361260	CLARK CO	HC	NO
213.	361280	CLERMONT CO	HC -24.9	NO
214.	361340	CLINTON CO	HC	NO
215.	361440	COLUMBIANA CO	HC	NO
216.	361520	COSHOCTON CO	HC	NO
217.	361540	CRAWFORD CO	HC	NO
218.	361600	CUYAHOGA CO	HC -18.9	NO
219.	361760	DELAWARE CO	HC	NO
220.	362000	ERIE CO	HC	NO
221.	362020	FAIRFIELD CO	HC	NO
222.	362140	FAYETTE CO	HC	NO
223.	362220	FRANKLIN CO	HC	NO
224.	362260	FULTON CO	HC	NO
225.	362300	GALLIA CO	HC	NO
226.	362330	GEAUGA CO	HC	NO

227.	362580	GREENE CO	HC		NO
228.	362680	GUERNSEY CO	HC		NO
229.	362740	HANCOCK CO	HC		NO
230.	362760	HARDIN CO	HC		NO
231.	362800	HARRISON CO	HC		NO
232.	362820	HENRY CO	HC		NO
233.	362860	HIGHLAND CO	HC		NO
234.	362940	HOCKING CO	HC		NO
235.	362960	HOLMES CO	HC		NO
236.	363020	HURON CO	HC		NO
237.	363120	JACKSON CO	HC		NO
238.	363160	JEFFERSON CO	HC		NO
239.	363260	KNOX CO	HC		NO
240.	363280	LAKE CO	HC	-8.6	NO
241.	363380	LAWRENCE CO	HC		NO
242.	363440	LICKING CO	HC		NO
243.	363580	LOGAN CO	HC		NO
244.	363640	LORAIN CO	HC	-10.7	NO
245.	363720	LUCAS CO	HC		NO
246.	363800	MADISON CO	HC		NO
247.	363820	MAHONING CO	HC		NO
248.	363960	MARION CO	HC		NO
249.	364160	MEDINA CO	HC	-19.6	NO
250.	364180	MEIGS CO	HC		NO
251.	364460	MONROE CO	HC		NO
252.	364540	MORGAN CO	HC		NO
253.	364560	MORROW CO	HC		NO
254.	364640	MUSKINGUM CO	HC		NO
255.	364900	NOBLE CO	HC		NO
256.	365260	OTTAWA CO	HC		NO
257.	365440	PERRY CO	HC		NO
258.	365480	PICKAWAY CO	HC		NO
259.	365500	PIKE CO	HC		NO
260.	365580	PORTAGE CO	HC		NO
261.	365660	PUTNAM CO	HC		NO
262.	365740	RICHLAND CO	HC		NO
263.	365840	ROSS CO	HC		NO
264.	365900	SANDUSKY CO	HC		NO
265.	366020	SCIOTO CO	HC		NO
266.	366060	SENECA CO	HC		NO
267.	366220	SHELBY CO	HC		NO
268.	366400	STARK CO	HC		NO
269.	366500	SUMMIT CO	HC		NO
270.	366780	TRUMBULL CO	HC		NO
271.	366720	TUSCARAWAS CO	HC		NO
272.	366780	UNION CO	HC		NO
273.	366960	VINTON CO	HC		NO
274.	367040	WARREN CO	HC	-35.0	NO
275.	367100	WASHINGTON CO	HC		NO
276.	367160	WAYNE CO	HC		NO
277.	367580	WOOD CO	HC		NO
278.	367660	WYANDOT CO	HC		NO
279.	390040	ADAMS CO	HC		NO
280.	390100	ALLEGHENY CO	HC	-39.3	NO
281.	390260	ARMSTRONG CO	HC	-39.3	NO
282.	390360	BEAVER CO	HC		NO
283.	390620	BEDFORD CO	HC		NO

284.	390720	BERKS CO	HC	NO
285.	390820	BLAIR CO	HC	NO
286.	391000	BRADFORD CO	HC	NO
287.	391200	BUCKS CO	HC -38.5	NO
288.	391260	BUTLER CO	HC -39.3	NO
289.	391300	CAMBRIA CO	HC	NO
290.	391320	CAMERON CO	HC	NO
291.	391380	CARBON CO	HC	NO
292.	391520	CENTRE CO	HC	NO
293.	391660	CHESTER CO	HC -38.5	NO
294.	391760	CLARION CO	HC	NO
295.	391820	CLEARFIELD CO	HC	NO
296.	391860	CLINTON CO	HC	NO
297.	391960	COLUMBIA CO	HC	NO
298.	392140	CRAWFORD CO	HC	NO
299.	392180	CUMBERLAND CO	HC	NO
300.	392340	DAUPHIN CO	HC	NO
301.	392360	DELAWARE CO	HC -38.5	NO
302.	392940	ELK CO	HC	NO
303.	393080	ERIE CO	HC	NO
304.	393220	FAYETTE CO	HC	NO
305.	393320	FOREST CO	HC	NO
306.	393480	FRANKLIN CO	HC	NO
307.	393540	FULTON CO	HC	NO
308.	393720	GREENE CO	HC	NO
309.	394200	HUNTINGDON CO	HC	NO
310.	394240	INDIANA CO	HC	NO
311.	394340	JEFFERSON CO	HC	NO
312.	394480	JUNIATA CO	HC	NO
313.	394640	LACKAWANNA CO	HC	NO
314.	394700	LANCASTER CO	HC	NO
315.	394840	LAWRENCE CO	HC	NO
316.	394900	LEBANON CO	HC	NO
317.	394940	LEHIGH CO	HC -36.1	NO
318.	395220	LUZERNE CO	HC	NO
319.	395240	LYCOMING CO	HC	NO
320.	395360	MC KEAN CO	HC	NO
321.	395660	MERCER CO	HC	NO
322.	395760	MIFFLIN CO	HC	NO
323.	395960	MONROE CO	HC	NO
324.	396000	MONTGOMERY CO	HC -38.5	NO
325.	396020	MONTOUR CO	HC	NO
326.	396580	NORTHAMPTON CO	HC -36.1	NO
327.	396700	NORTHUMBERLAND CO	HC	NO
328.	397120	PERRY CO	HC	NO
329.	397160	PHILADELPHIA CO	HC -38.5	NO
330.	397220	PIKE CO	HC	NO
331.	397460	POTTER CO	HC	NO
332.	397960	SCHUYLKILL CO	HC	NO
333.	398320	SNYDER CO	HC	NO
334.	398360	SOMERSET CO	HC	NO
335.	398740	SULLIVAN CO	HC	NO
336.	398800	SUSQUEHANNA CO	HC	NO
337.	399000	TIOGA CO	HC	NO
338.	399070	UNION CO	HC	NO
339.	399140	VENANGO CO	HC	NO
340.	399180	WARREN CO	HC	NO

341.	399200	WASHINGTON CO	HC -39.3	NO
342.	399220	WAYNE CO	HC	NO
343.	399330	WESTMORELAND CO	HC -39.3	NO
344.	399530	WYOMING CO	HC	NO
345.	399570	YORK CO	HC	NO
346.	410060	BRISTOL CO	HC -3.9	NO
347.	410140	KENT CO	HC -3.9	NO
348.	410200	NEWPORT CO	HC -3.9	NO
349.	410320	PROVIDENCE CO	HC -3.9	NO
350.	410380	WASHINGTON CO	HC -3.9	NO
351.	470020	ADDISON CO	HC	NO
352.	470100	BENNINGTON CO	HC	NO
353.	470160	CALEDONIA CO	HC	NO
354.	470180	CHITTENDEN CO	HC	NO
355.	470200	ESSEX CO	HC	NO
356.	470240	FRANKLIN CO	HC	NO
357.	470260	GRAND ISLE CO	HC	NO
358.	470280	LAMOILLE CO	HC	NO
359.	470360	ORANGE CO	HC	NO
360.	470380	ORLEANS CO	HC	NO
361.	470420	RUTLAND CO	HC	NO
362.	470500	WASHINGTON CO	HC	NO
363.	470580	WINDHAM CO	HC	NO
364.	470620	WINDSOR CO	HC	NO
365.	480040	ACCOMACK CO	HC	NO
366.	480060	ALBEMARLE CO	HC	NO
367.	480200	ARLINGTON CO	HC -42.4	NO
368.	480260	AUGUSTA CO	HC	NO
369.	480300	BATH CO	HC	NO
370.	480600	CAROLINE CO	HC	NO
371.	480760	CLARKE CO	HC	NO
372.	480880	CULPEPER CO	HC	NO
373.	481000	ESSEX CO	HC	NO
374.	481060	FAIRFAX CO	HC -30.9	NO
375.	480080	FAIRFAX CO	HC -30.9	NO
376.	481120	FAUQUIER CO	HC	NO
377.	481220	FREDERICK CO	HC	NO
378.	481360	GREENE CO	HC	NO
379.	481460	HANOVER CO	HC	NO
380.	481540	HIGHLAND CO	HC	NO
381.	481640	KING GEORGE CO	HC	NO
382.	481760	LOUDOUN CO	HC -10.5	NO
383.	481780	LOUISA CO	HC	NO
384.	481860	MADISON CO	HC	NO
385.	482020	NELSON CO	HC	NO
386.	482200	NORTHUMBERLAND CO	HC	NO
387.	482300	ORANGE CO	HC	NO
388.	482320	PAGE CO	HC	NO
389.	482520	PRINCE WILLIAM CO	HC -33.5	NO
390.	482620	RAPPAHANNOCK CO	HC	NO
391.	482680	RICHMOND CO	HC	NO
392.	482740	ROCKERIDGE CO	HC	NO
393.	482760	ROCKINGHAM CO	HC	NO
394.	482880	SHENANDOAH CO	HC	NO
395.	483000	SPOTSYLVANIA CO	HC	NO
396.	483040	STAFFORD CO	HC	NO
397.	483260	WARREN CO	HC	NO

398.	483340	WESTMORELAND CO	HC	NO
399.	500020	BARBOUR CO	HC	NO
400.	500100	BERKELEY CO	HC	NO
401.	500140	BOONE CO	HC	NO
402.	500160	BRAXTON CO	HC	NO
403.	500200	BROOKE CO	HC	NO
404.	500240	CABELL CO	HC	NO
405.	500260	CALHOUN CO	HC	NO
406.	500380	CLAY CO	HC	NO
407.	500400	DODDRIDGE CO	HC	NO
408.	500460	FAYETTE CO	HC	NO
409.	500520	GILMER CO	HC	NO
410.	500560	GRANT CO	HC	NO
411.	500580	GREENBRIER CO	HC	NO
412.	500600	HAMPSHIRE CO	HC	NO
413.	500620	HANCOCK CO	HC	NO
414.	500640	HARDY CO	HC	NO
415.	500660	HARRISON CO	HC	NO
416.	500720	JACKSON CO	HC	NO
417.	500740	JEFFERSON CO	HC	NO
418.	500760	KANAWHA CO	HC	NO
419.	500840	LEWIS CO	HC	NO
420.	500860	LINCOLN CO	HC	NO
421.	500900	LOGAN CO	HC	NO
422.	500980	MARION CO	HC	NO
423.	501020	MARSHALL CO	HC	NO
424.	501060	MASON CO	HC	NO
425.	501100	MINERAL CO	HC	NO
426.	501140	MONONGALIA CO	HC	NO
427.	501200	MORGAN CO	HC	NO
428.	501320	NICHOLAS CO	HC	NO
429.	501360	OHIO CO	HC	NO
430.	501440	PENDLETON CO	HC	NO
431.	501460	PLEASANTS CO	HC	NO
432.	501480	POCAHONTAS CO	HC	NO
433.	501520	PRESTON CO	HC	NO
434.	501560	PUTNAM CO	HC	NO
435.	501600	RANDOLPH CO	HC	NO
436.	501680	RITCHIE CO	HC	NO
437.	501700	ROANE CO	HC	NO
438.	501840	TAYLOR CO	HC	NO
439.	501860	TUCKER CO	HC	NO
440.	501880	TYLER CO	HC	NO
441.	501900	UPSHUR CO	HC	NO
442.	501960	WAYNE CO	HC	NO
443.	501980	WEBSTER CO	HC	NO
444.	502100	WETZEL CO	HC	NO
445.	502200	WIRT CO	HC	NO
446.	502220	WOOD CO	HC	NO

END DATA.

APPENDIX B

COUNTIES GROUPED BY LAND USE

Counties in the Northeastern United States categorized according to land use into four groups: Major Source; Non-major Source Metropolitan Statistical Areas (MSAs); Agricultural; and Natural. The first group comprises the top-fifty VOC and NO_x emissions density counties shown in Figure 3, page 16. The first two groups of counties are considered MSAs in the analyses presented in Section 6, and the agricultural and natural counties are treated as non-MSAs.

Major Source Counties

STATENM	COUNTYNM
CONNECTICUT	FAIRFIELD
CONNECTICUT	HARTFORD
CONNECTICUT	NEW HAVEN
DELAWARE	NEW CASTLE
DIST. COLUMBIA	DISTRICT OF COLUMBIA
MARYLAND	ANNE ARUNDEL
MARYLAND	BALTIMORE CITY
MARYLAND	BALTIMORE
MARYLAND	PRINCE GEORGES
MASSACHUSETTS	DUKES
MASSACHUSETTS	MIDDLESEX
MASSACHUSETTS	NORFOLK
MASSACHUSETTS	SUFFOLK
MICHIGAN	BAY
MICHIGAN	GENESEE
MICHIGAN	MACOMB
MICHIGAN	MONROE
MICHIGAN	OAKLAND
MICHIGAN	WAYNE
NEW JERSEY	BERGEN
NEW JERSEY	CAMDEN
NEW JERSEY	ESSEX
NEW JERSEY	GLOUCESTER
NEW JERSEY	HUDSON
NEW JERSEY	MERCER
NEW JERSEY	MIDDLESEX
NEW JERSEY	MORRIS
NEW JERSEY	PASSAIC
NEW JERSEY	UNION
NEW YORK	ALBANY
NEW YORK	BRONX
NEW YORK	KINGS
NEW YORK	NASSAU
NEW YORK	NEW YORK
NEW YORK	QUEENS
NEW YORK	RICHMOND
NEW YORK	ROCKLAND
NEW YORK	WESTCHESTER

STATENM	COUNTYNM
OHIO	ADAMS
OHIO	CUYAHOGA
OHIO	FRANKLIN
OHIO	GALLIA
OHIO	JEFFERSON
OHIO	LAKE
OHIO	LORAIN
OHIO	LUCAS
OHIO	SUMMIT
OHIO	WASHINGTON
PENNSYLVANIA	ALLEGHENY
PENNSYLVANIA	ARMSTRONG
PENNSYLVANIA	BEAVER
PENNSYLVANIA	BUCKS
PENNSYLVANIA	DELAWARE
PENNSYLVANIA	INDIANA
PENNSYLVANIA	MONTGOMERY
PENNSYLVANIA	MONTOUR
PENNSYLVANIA	NORTHAMPTON
PENNSYLVANIA	PHILADELPHIA
PENNSYLVANIA	VENANGO
RHODE ISLAND	BRISTOL
RHODE ISLAND	KENT
RHODE ISLAND	PROVIDENCE
VIRGINIA	ARLINGTON
VIRGINIA	FAIRFAX
WEST VIRGINIA	HANCOCK
WEST VIRGINIA	HARRISON
WEST VIRGINIA	MARSHALL
WEST VIRGINIA	MASON
WEST VIRGINIA	MONONGALIA
WEST VIRGINIA	PUTNAM

Non-Major Source SMSA Counties
(Suburban Counties)

STATENM	COUNTYNM
CONNECTICUT	MIDDLESEX
CONNECTICUT	NEW LONDON
CONNECTICUT	TOLLAND
KENTUCKY	BOYD
KENTUCKY	GREENUP
MAINE	ANDROSCOGGIN
MAINE	CUMBERLAND
MAINE	PENOBSCOT
MAINE	SAGADAHOC
MAINE	YORK
MARYLAND	ALLEGANY
MARYLAND	CARROLL
MARYLAND	CECIL
MARYLAND	CHARLES
MARYLAND	HARFORD
MARYLAND	MONTGOMERY
MARYLAND	WASHINGTON
MASSACHUSETTS	BERKSHIRE
MASSACHUSETTS	BRISTOL
MASSACHUSETTS	ESSEX
MASSACHUSETTS	HAMPDEN
MASSACHUSETTS	HAMPSHIRE
MASSACHUSETTS	PLYMOUTH
MASSACHUSETTS	WORCESTER
MICHIGAN	LAPEER
MICHIGAN	LIVINGSTON
MICHIGAN	SAGINAW
MICHIGAN	ST CLAIR
MICHIGAN	SHIAWASSEE
MICHIGAN	WASHTENAW
NEW HAMPSHIRE	HILLSBOROUGH
NEW HAMPSHIRE	ROCKINGHAM
NEW HAMPSHIRE	STRAFFORD
NEW JERSEY	ATLANTIC
NEW JERSEY	BURLINGTON
NEW JERSEY	CUMBERLAND
NEW JERSEY	MONMOUTH
NEW JERSEY	SALEM
NEW JERSEY	SOMERSET
NEW JERSEY	WARREN
NEW YORK	BROOME
NEW YORK	CHEMUNG
NEW YORK	DUTCHESS
NEW YORK	ERIE
NEW YORK	HERKIMER
NEW YORK	LIVINGSTON
NEW YORK	MADISON
NEW YORK	MONROE
NEW YORK	MONTGOMERY
NEW YORK	NIAGARA
NEW YORK	ONEIDA
NEW YORK	ONONDAGA
NEW YORK	ONTARIO
NEW YORK	ORANGE
NEW YORK	ORLEANS
NEW YORK	OSWEGO
NEW YORK	PUTNAM
NEW YORK	RENSSELAER
NEW YORK	SARATOGA
NEW YORK	SCHENECTADY
NEW YORK	SUFFOLK
NEW YORK	TIOGA
NEW YORK	WARREN
NEW YORK	WASHINGTON
NEW YORK	WAYNE
OHIO	ALLEN
OHIO	AUGLAIZE
OHIO	BELMONT
OHIO	CARROLL
OHIO	CHAMPAIGN
OHIO	CLARK
OHIO	CLERMONT
OHIO	DELAWARE
OHIO	FAIRFIELD
OHIO	FULTON
OHIO	GEAUGA
OHIO	GREENE
OHIO	LAWRENCE
OHIO	LICKING
OHIO	MADISON
OHIO	MAHONING
OHIO	MEDINA
OHIO	OTTAWA
OHIO	PICKAWAY
OHIO	PORTAGE
OHIO	PUTNAM
OHIO	RICHLAND
OHIO	STARK
OHIO	TRUMBULL
OHIO	WARREN
OHIO	WOOD
PENNSYLVANIA	ADAMS
PENNSYLVANIA	BERKS
PENNSYLVANIA	CAMBRIA
PENNSYLVANIA	CARBON
PENNSYLVANIA	CENTRE
PENNSYLVANIA	CHESTER
PENNSYLVANIA	CUMBERLAND
PENNSYLVANIA	DAUPHIN
PENNSYLVANIA	ERIE
PENNSYLVANIA	LACKAWANNA
PENNSYLVANIA	LANCASTER
PENNSYLVANIA	LEHIGH
PENNSYLVANIA	LUZERNE
PENNSYLVANIA	LYCOMING
PENNSYLVANIA	MONROE
PENNSYLVANIA	PERRY
PENNSYLVANIA	SOMERSET
PENNSYLVANIA	SUSQUEHANNA
PENNSYLVANIA	WASHINGTON
PENNSYLVANIA	WESTMORELAND
PENNSYLVANIA	YORK
RHODE ISLAND	WASHINGTON
VERMONT	CHITTENDEN
VIRGINIA	ALBEMARLE
VIRGINIA	GREENE
VIRGINIA	HANOVER
VIRGINIA	LOUDOUN
VIRGINIA	PRINCE WILLIAM
VIRGINIA	RICHMOND
WEST VIRGINIA	BROOKE
WEST VIRGINIA	CABELL
WEST VIRGINIA	KANAWHA
WEST VIRGINIA	MINERAL
WEST VIRGINIA	OHIO
WEST VIRGINIA	WAYNE
WEST VIRGINIA	WIRT
WEST VIRGINIA	WOOD

Agricultural Counties

STATENM	COUNTYNM
DELAWARE	KENT
KENTUCKY	BATH
KENTUCKY	BOURBON
KENTUCKY	BRACKEN
KENTUCKY	FLEMING
KENTUCKY	MASON
KENTUCKY	MONTGOMERY
KENTUCKY	NICHOLAS
KENTUCKY	ROBERTSON
MARYLAND	CAROLINE
MARYLAND	FREDERICK
MARYLAND	HOWARD
MARYLAND	KENT
MARYLAND	QUEEN ANNES
MARYLAND	TALBOT
MASSACHUSETTS	NANTUCKET
MICHIGAN	HURON
MICHIGAN	LENAWEE
MICHIGAN	SANILAC
MICHIGAN	TUSCOLA
NEW JERSEY	HUNTERDON
NEW YORK	CAYUGA
NEW YORK	GENESEE
NEW YORK	JEFFERSON
NEW YORK	SCHUYLER
NEW YORK	SENECA
NEW YORK	STEUBEN
NEW YORK	TOMPKINS
NEW YORK	WYOMING
NEW YORK	YATES
OHIO	ASHLAND
OHIO	ASHTABULA
OHIO	BROWN
OHIO	CLINTON
OHIO	COLUMBIANA
OHIO	COSHOCTON
OHIO	CRAWFORD
OHIO	ERIE
OHIO	FAYETTE
OHIO	GUERNSEY
OHIO	HANCOCK
OHIO	HARDIN
OHIO	HARRISON
OHIO	HENRY
OHIO	HIGHLAND
OHIO	HOLMES
OHIO	HURON
OHIO	KNOX
OHIO	LOGAN
OHIO	MARION
OHIO	MORGAN
OHIO	MORROW
OHIO	MUSKINGUM
OHIO	NOBLE
OHIO	SANDUSKY
OHIO	SENECA
OHIO	SHELBY
OHIO	TUSCARAWAS
OHIO	UNION
OHIO	WAYNE
OHIO	WYANDOT
PENNSYLVANIA	BRADFORD
PENNSYLVANIA	COLUMBIA
PENNSYLVANIA	CRAWFORD
PENNSYLVANIA	FRANKLIN
PENNSYLVANIA	GREENE
PENNSYLVANIA	LAWRENCE
PENNSYLVANIA	LEBANON
PENNSYLVANIA	MERCER
PENNSYLVANIA	NORTHUMBERLAND
VIRGINIA	CLARKE
WEST VIRGINIA	BARBOUR
WEST VIRGINIA	JEFFERSON
WEST VIRGINIA	MARION
WEST VIRGINIA	TAYLOR

Natural Counties

STATENM	COUNTYNM
CONNECTICUT	LITCHFIELD
CONNECTICUT	WINDHAM
DELAWARE	SUSSEX
KENTUCKY	CARTER
KENTUCKY	ELLIOTT
KENTUCKY	LAWRENCE
KENTUCKY	LEWIS
KENTUCKY	MENIFEE
KENTUCKY	MORGAN
KENTUCKY	ROWAN
MAINE	FRANKLIN
MAINE	KENNEBEC
MAINE	KNOX
MAINE	LINCOLN
MAINE	OXFORD
MAINE	SOMERSET
MAINE	WALDO
MARYLAND	CALVERT
MARYLAND	DORCHESTER
MARYLAND	GARRETT
MARYLAND	ST MARYS
MARYLAND	SOMERSET
MARYLAND	WICOMICO
MARYLAND	WORCESTER
MASSACHUSETTS	BARNSTABLE
MASSACHUSETTS	FRANKLIN
MICHIGAN	ALCONA
MICHIGAN	ALPENA
MICHIGAN	ARENAC
MICHIGAN	IOSCO
MICHIGAN	MONTMORENCY
MICHIGAN	OGEMAW
MICHIGAN	OSCODA
NEW HAMPSHIRE	BELKNAP
NEW HAMPSHIRE	CARROLL
NEW HAMPSHIRE	CHESHIRE
NEW HAMPSHIRE	COOS
NEW HAMPSHIRE	GRAFTON
NEW HAMPSHIRE	MERRIMACK
NEW HAMPSHIRE	SULLIVAN
NEW JERSEY	CAPE MAY
NEW JERSEY	OCEAN
NEW JERSEY	SUSSEX
NEW YORK	ALLEGANY
NEW YORK	CATTARAUGUS
NEW YORK	CHAUTAUQUA
NEW YORK	CHENANGO
NEW YORK	CLINTON
NEW YORK	COLUMBIA
NEW YORK	CORTLAND
NEW YORK	DELAWARE
NEW YORK	ESSEX
NEW YORK	FRANKLIN
NEW YORK	FULTON
NEW YORK	GREENE
NEW YORK	HAMILTON
NEW YORK	LEWIS
NEW YORK	OTSEGO
NEW YORK	ST LAWRENCE
NEW YORK	SCHOHARIE
NEW YORK	SULLIVAN
NEW YORK	ULSTER
OHIO	ATHENS
OHIO	HOCKING
OHIO	JACKSON
OHIO	MEIGS
OHIO	MONROE
OHIO	PERRY
OHIO	PIKE
OHIO	ROSS
OHIO	SCIOTO
OHIO	VINTON
PENNSYLVANIA	BEDFORD
PENNSYLVANIA	BLAIR
PENNSYLVANIA	BUTLER
PENNSYLVANIA	CAMERON
PENNSYLVANIA	CLARION
PENNSYLVANIA	CLEARFIELD
PENNSYLVANIA	CLINTON

Natural Counties, continued

STATENM	COUNTYNM
PENNSYLVANIA	ELK
PENNSYLVANIA	FAYETTE
PENNSYLVANIA	FOREST
PENNSYLVANIA	FULTON
PENNSYLVANIA	HUNTINGDON
PENNSYLVANIA	JEFFERSON
PENNSYLVANIA	JUNIATA
PENNSYLVANIA	MC KEAN
PENNSYLVANIA	MIFFLIN
PENNSYLVANIA	PIKE
PENNSYLVANIA	POTTER
PENNSYLVANIA	SCHUYLKILL
PENNSYLVANIA	SNYDER
PENNSYLVANIA	SULLIVAN
PENNSYLVANIA	TIOGA
PENNSYLVANIA	UNION
PENNSYLVANIA	WARREN
PENNSYLVANIA	WAYNE
PENNSYLVANIA	WYOMING
RHODE ISLAND	NEWPORT
VERMONT	ADDISON
VERMONT	BENNINGTON
VERMONT	CALEDONIA
VERMONT	ESSEX
VERMONT	FRANKLIN
VERMONT	GRAND ISLE
VERMONT	LAMOILLE
VERMONT	ORANGE
VERMONT	ORLEANS
VERMONT	RUTLAND
VERMONT	WASHINGTON
VERMONT	WINDHAM
VERMONT	WINDSOR
VIRGINIA	ACCOMACK
VIRGINIA	AUGUSTA
VIRGINIA	BATH
VIRGINIA	CAROLINE
VIRGINIA	CULPEPER
VIRGINIA	ESSEX
VIRGINIA	FAUQUIER
VIRGINIA	FREDERICK
VIRGINIA	HIGHLAND
VIRGINIA	KING GEORGE
VIRGINIA	LOUISA
VIRGINIA	MADISON
VIRGINIA	NELSON
VIRGINIA	NORTHUMBERLAND
VIRGINIA	ORANGE
VIRGINIA	PAGE
VIRGINIA	RAPPAHANNOCK
VIRGINIA	ROCKBRIDGE
VIRGINIA	ROCKINGHAM
VIRGINIA	SHENANDOAH
VIRGINIA	SPOTSYLVANIA
VIRGINIA	STAFFORD
VIRGINIA	WARREN
VIRGINIA	WESTMORELAND
WEST VIRGINIA	BERKELEY
WEST VIRGINIA	BOONE
WEST VIRGINIA	BRAXTON
WEST VIRGINIA	CALHOUN
WEST VIRGINIA	CLAY
WEST VIRGINIA	DODDRIDGE
WEST VIRGINIA	FAYETTE
WEST VIRGINIA	GILMER
WEST VIRGINIA	GRANT
WEST VIRGINIA	GREENBRIER
WEST VIRGINIA	HAMPSHIRE
WEST VIRGINIA	HARDY
WEST VIRGINIA	JACKSON
WEST VIRGINIA	LEWIS
WEST VIRGINIA	LINCOLN
WEST VIRGINIA	LOGAN
WEST VIRGINIA	MORGAN
WEST VIRGINIA	NICHOLAS
WEST VIRGINIA	PENDLETON
WEST VIRGINIA	PLEASANTS
WEST VIRGINIA	POCAHONTAS
WEST VIRGINIA	PRESTON
WEST VIRGINIA	RANDOLPH
WEST VIRGINIA	RITCHIE
WEST VIRGINIA	ROANE
WEST VIRGINIA	TUCKER
WEST VIRGINIA	TYLER
WEST VIRGINIA	UPSHUR
WEST VIRGINIA	WEBSTER
WEST VIRGINIA	WETZEL